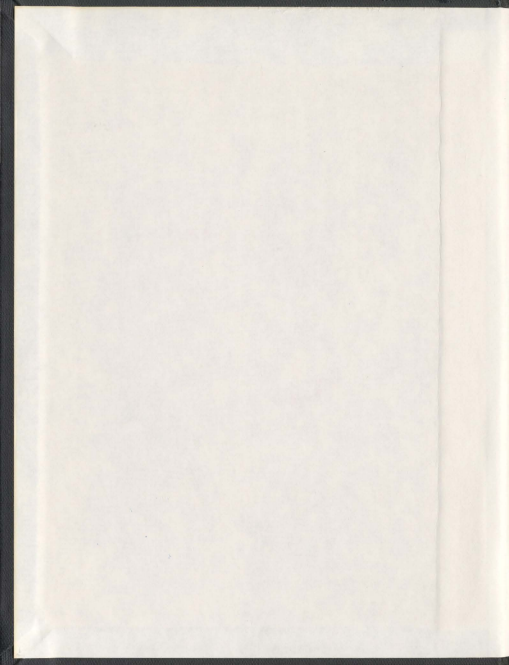


MODELLING THE INFLUENCE OF NEIGHBOURHOOD
DESIGN ON DAILY TRIP PATTERNS IN URBAN
NEIGHBOURHOODS

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Modelling the Influence of Neighbourhood Design on
Daily Trip Patterns in Urban Neighbourhoods

by

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ABSTRACT

To solve problems such as traffic congestion, air pollution, overreliance on the automobile, limited access to transit and reduced social interaction which are often associated with post-war suburban neighbourhood design, several new neighbourhood designs have been proposed, including the neo-traditional (New Urbanism) and the fused grid designs. This study examines the influence of different neighbourhood designs on daily trip patterns in urban neighbourhoods using agent-based computer simulation. An agent based neighbourhood level traffic simulation model, together with the associated software is developed, and the model is calibrated based on maps and data from Ottawa, Ontario. With consideration of personal characteristics, preferences and feedbacks between pedestrian and automobile traffic, the model combines the advantages of utility-based, activity-based and constraint-based approaches, and proves able to generate realistic trip patterns. Experiments are carried out using the calibrated model to explore the influence of different types of neighbourhood design as well as the influence of detailed design features such as the availability of pedestrian-only routes and the location of facilities. Results from the experiments show that the neo-traditional and fused grid designs are generally pedestrian friendly, with fewer crossings, less walking distance to facilities, less traffic and exposure to pollution and more social interaction opportunities for pedestrians; but some of these advantages also depend on the specific implementation. The study shows the promise of a meso-level approach to urban and transportation simulation.

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LIST OF FREQUENTLY USED ABBREVEIATIONS

ABM: Agent-based modelling, agent-based model

CA: Cellular Automata

FG: Fused grid

MAS: Multi-agent system

MNL: Multinomial Logistic

NU: New Urbanism

POR: Pedestrian-only route

PW: Post-war suburban

TAZ: Traffic analysis zone

TG: Traditional grid

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CHAPTER 1: INTRODUCTION

With a majority of the population living in urban areas in North America and Europe, and fast growing urban populations in other parts of the world, urban problems have become one of the most important phenomena directly related to our daily lives. Problems such as traffic congestion, parking availability, air pollution and greenhouse gas emissions, access to public transit and other community facilities, and overreliance on automobiles directly influence our life patterns and quality of life. These seemingly local phenomena are also directly related to global issues such as climate change and sustainable development. Various efforts have been made to improve the situation, with measures such as increasing the availability of public transit and community facilities, discouraging private car use through different forms of fees or taxes, and making more energy efficient and environmentally friendly cars. Still, urban and transportation planning is by far the most direct and influential approach. It is broadly recognized that land use and transportation interact with each other, and that land use, transportation facilities and city residents form a complex system. An integrated planning approach is needed for such a system. Integrated land use and transportation planning has been in effect in various areas, along with intensive research in this field (Timmermans, 2003).

Urban neighbourhoods are the basic units of cities. As city residents spend most of their personal life inside residential neighbourhoods, neighbourhood designs are also directly related to daily life patterns and quality of life. The design of an urban neighbourhood directly determines its local road networks and facility locations, directly

influences route choices and facility accessibility for local residents and indirectly influences choices of transport mode. Local streets play an important part in daily lives. They are not only roads for driving, walking and exercising, but also important places for social interaction between local residents. Thus, neighbourhood design is an essential part of integrated land use and transportation planning.

Neighbourhood design has been evolving to suit the needs of the times. Before the appearance of personal automobiles, the grid layout was the most prevalent city and street layout plan. Such a layout is simple to design, yet provides good accessibility for pedestrians to access facilities and (later) street cars. Since the beginning of the 20th century, with personal automobiles more widely used, layouts that suit the needs of automobile owners began to be implemented in newly developed suburban areas. These layouts often feature large blocks, low densities, separation of residential and other land uses, and extensive use of cul-de-sacs and hierarchical street systems. Since the 1980s, with more focus on and better understanding of existing urban problems, many new designs and theories have been proposed. The compact city theory, neo-traditional neighbourhood developments, and the recently proposed fused grid design, all claim to be able to solve certain urban problems associated with the automobile-oriented designs.

Evaluation and modelling of urban plans and neighbourhood designs have been important research fields in urban studies, with the latest attempts being modelling sustainability in Canadian cities using integrated urban models (Hatzopoulou and Miller, 2006; Maoh and Kanaroglou, 2006; Behan *et al.* 2008). While different planning approaches have been explored along with related projects and simulation models, the

majority of these models focus on the regional or metropolitan scale, with little or no consideration of individuals and local processes. Comparisons of neighbourhood designs and their influence have also been carried out for various places. But most of the existing literature in this field relies on aggregate or macro-scale simulation, simulation that ignores personal preference and choice, description or statistical analysis (Boarnet and Crane, 2001a, 2001b).

Like cities, neighbourhoods are also complex systems, with local residents acting on their own intentions and decisions, and interacting with each other in the transportation systems. While traditional research methods like aggregate statistical analysis and equation-based methods can be used to analyze certain aspects of such a complex system, they often fail to explain many essential aspects such as local interactions, feedback processes, and emergence and bifurcation behaviour. For a better understanding of such an individual-based system, an individual-based research approach which focuses on bottom-up processes and local dynamics should be taken. The aggregate and macro-scale approaches that are used in most existing studies not only limit the understanding of local dynamics inside the neighbourhood, but also make it impossible to evaluate newly proposed theories like the fused grid design, for which no real-world aggregate data are available.

A suitable individual-based research approach is agent-based modelling (ABM). In an agent-based model, agents, through their own characteristics and intentions, and by getting information from the environment, make their own decisions. The collective outcome of these decisions forms the dynamics of the whole system. Agent-based models

have been widely used in urban and transportation simulations, but most models focus on either automobiles on the highway system, or pedestrians in an enclosed environment (for example, streets, parks, rooms, buildings, and underground passages).

In this study, an agent-based model is proposed to simulate both automobile and pedestrian movements in urban neighbourhoods, with emphasis on pedestrian movements and the associated benefits or risks. The model is designed to discover how neighbourhood designs influence route and mode choice of local residents, how the collective outcome of individual choices influences trip and traffic patterns, and how these patterns in turn influence certain aspects of residents' daily lives such as health and social opportunities.

The thesis is organized into the following chapters: Chapter 2 provides an introduction and a literature review of the evolution of neighbourhood designs, the existing research on how neighbourhood designs influence different aspects of urban life, and the existing approaches of modelling cities and transportation systems. Chapter 3 explains the underlying methodologies of this study. Chapter 4 describes the process of building a software platform that is able to carry out neighbourhood level transportation simulation using trip survey data and GIS maps. In Chapters 5 and 6, a model based on the software platform as well as data and maps from the city of Ottawa is proposed and calibrated. The model is then used in Chapter 7 to compare four types of neighbourhood designs including traditional grid, post-war suburban, neo-traditional development and fused grid. Conclusions and further research directions are discussed in Chapter 8.

CHAPTER 2: LITERATURE REVIEW

2.1 EVOLUTION OF NEIGHBOURHOOD FORMS

A city's form and structure change with its development, growth and expansion. The form and structure of its residential neighbourhoods also change over time. Cities in North America share a more or less similar pattern of change. The traditional grid design (Figure 2.1) fits the age of streetcars, when cities expanded along the routes of the streetcar systems. While it is suggested that the grid design was applied primarily because the grid design made it easier to survey and record deeds and enabled the land owner to divide an area into as many lots as possible (Ryan and McNally, 1995), the design practically met the needs of pedestrians for better access to transit stops.

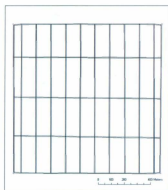


Figure 2.1: Example of a traditional grid neighbourhood

The rise of automobile use led to the design of automobile-oriented neighbourhoods (Figure 2.2). A famous example is the first American Garden City, the town of Radburn, New Jersey, "a town for the motor age" (The Town of Radburn website). The large size of the block, the use of cul-de-sacs and a hierarchical street system, and the separation of residential land use from commercial, industrial and other land uses all discourage pedestrian movement and favour automobile use. The original Radburn plan did include a pedestrian path and parklands system accessible from every home, which enables the separation of traffic by mode and promotes safety, but because of the street design standards adopted by the U.S. Federal Housing Administration (FHA) (Zhang and Yi, 2006), and because of developers' consideration for land use efficiencies and economic benefits (Canada Housing and Mortgage Corporation (CMHC), 2002; Zhang and Yi, 2006), most of the later implementations of the plan in other areas eliminated the pedestrian and parklands system.

The post-war development of cities, especially in the USA, was characterized by massive urban sprawl which was enabled by funded federal projects including highway construction and home mortgage insurance (Ryan and McNally, 1995; Stanilov, 2002). With the key considerations of post-war planning being density, efficient layout and cost (Evans and Larkham, 2004), cul-de-sacs were favoured over grids because research showed that the former has better efficiency in land use, with 16 to 25 percent less land required, mainly due to a much lower percentage of land needed for roads and streets (CMHC, 2002).

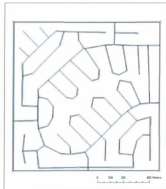


Figure 2.2: Example of a post-war suburban neighbourhood with cul-de-sacs and looping roads

Problems such as traffic congestion, access to parking outside urban neighbourhoods, and the lack of access to facilities and public transit inside urban neighbourhoods, led to criticism of automobile-oriented planning. Beginning in the 1960s, planned unit development (PUD) and cluster development became predominant. In a PUD, an integrated community, instead of an individual lot, became the unit for planning. Normally two or more types of land uses such as housing, recreation, commercial and industrial land uses exist in a PUD, with residential land use clustered around public and common open space. The hierarchical street system is often used in PUD, with local streets serving only local residents and collector streets connecting local streets to arterials. Sidewalks are provided on at least one side of every street, and together with pedestrian ways, link residential area, open space and other land uses.

Curvilinear streets (which provide variety and changing street vista) and cul-de-sacs (which discourage speeding and promote quiet and safety) are also used in many PUD neighbourhoods (Rohe, 2009). Cluster development has most of the features of PUD, but focuses more on the efficient use of space to reduce land consumption and cost (Ryan and McNally, 1995). While both PUD and cluster development feature development of integrated communities with amenities and facilities such as schools, shopping and churches built in, residential land use is still well separated from other land uses inside the community. The use of curvilinear and cul-de-sac street patterns also inhibit connectivity, and favours automobile use over pedestrian.

With the continuing problems associated with the automobile-oriented designs, and amid the rising concerns on sustainable development and climate change in the 1980s and 1990s, various alternative urban theories and neighbourhood designs have been proposed. Examples are the theory of the compact city, neo-traditional neighbourhood development and the recently proposed fused grid design. These theories and designs try to provide a balance among walking, mass transit and automobile use.

Outside the world of planning, it was initially hypothesized that with the advances in telecommunication, telecommuting, teleshopping and other telecommunication-based activities would decrease the need for out-of-home travel. However, research shows that telecommuting reduces the frequency of travel but increases the distance of commute (Moos and Skaburskis, 2007). Total travel distance is still lower than it would be without telecommuting, but the contribution is not as significant as might have been expected

(Mokhtarian *et al.* 2004; Paez and Scott, 2007). Research also shows that teleshopping households engage in more shopping trips than other households (Ferrell, 2004).

In the proposed alternatives, one of the most influential theories is the theory of the compact city. The compact city was proposed by Dantzig and Saaty (1973). It is designed to enhance the quality of life, but not at the expense of the next generation (Jabareen, 2006). The basic idea is to encourage high density and mixed land use, hoping that a higher population density would make public transit feasible and mixed land use would reunite the places of work and living. The effectiveness of compact city policy is debated. Studies show that high densities could discourage car use (Kwok and Yeh, 2004), but the effect may only be evident when combined with other factors such as proximity to quality transit service and large concentration of activity opportunities (Filion *et al.* 2006). Furthermore, even with mixed land use, people do not necessarily seek jobs nearby (Matt *et al.* 2005). There is also no agreement on how dense an area should be or what kind of social and environmental issues may arise from too dense an area (Kwok and Yeh, 2004). Nonetheless, compact city theory shed a new light on the direction of planning. Conventional planning tends to plan towns and cities at a larger scale, while in the compact city theory, with the local community/neighbourhood seen as the basic level of provision, local and human scale factors are given greater emphasis (Kii and Doi, 2005).

Neo-traditional development is a recent neighbourhood design approach. Neo-traditional development promotes compact land use and social interaction in town centers. The idea has been applied to various master planning schemes in the United States and

Canada (CMHC, 2004). A famous example of neo-traditional development is Seaside, Florida designed by Duany and Plater-Zyberk, even though Seaside is now more like a resort than a residential neighbourhood (Garvin, 1996). A grid like network structure is promoted in neo-traditional developments, because it is found that a grid network provides shorter walking access to facilities (Congress for the New Urbanism (CNU), 2001) and better traffic flow (Duany and Plater-Zyberk, 1992). In practice, a modified grid with "T" intersections and street deflections is often used for traffic calming.

Neo-traditional development is the real world outcome of the New Urbanism movement, and the two terms are often used interchangeably in the literature (for example, see Lund, 2002; Berke *et al.* 2003; Southworth, 2003; Jabareen, 2006). However, it is pointed out in some research that New Urbanism is an umbrella term encompassing neo-traditional town planning, pedestrian pockets (which covers mixed land use and transit-centered design) and transit-oriented design (Bohl, 2000), or one encompassing neo-traditional design (NTD), transit oriented development (TOD), Smart Growth and even certain elements from sustainable development (Southworth, 2003). Or, as pointed out by CNU (2001), while New Urbanism has its roots in compact city theory, it has a wider scope and a more detailed agenda. New Urbanism covers the design of cities, the restoration and reconfiguration of existing urban centers and suburbs and even the architecture and landscape of individual buildings. Despite the name difference, these approaches under the umbrella of New Urbanism share common principles of building neighbourhoods that are diverse, compact, mixed use, pedestrian-oriented and transit-friendly (Bohl, 2000). Figure 2.3 shows an example of a neo-traditional neighbourhood

which shows the use of the grid network, the T-intersections and a continuous pedestrian-only path system jointly formed by the pedestrian-only routes and the garage access roads.

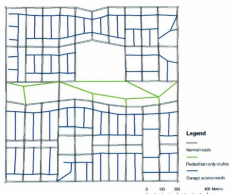


Figure 2.3: Example of a neo-traditional neighbourhood

Compared to the standard of a compact city, a neo-traditional development generally has lower density (Jabareen, 2006), and can be seen as a compromise between post-war suburban development and the compact city. This low-density feature of neo-traditional development is often criticized for being not sufficient to support mixed use and mass transit (Beatley, 2000; Southworth, 2003; Jabareen, 2006). Neo-traditional development is also criticized for the high cost of road system maintenance, snow removal and garbage pickup (CMHC, 2004).

Recently, the fused grid design (Figure 2.4), which claims to combine the advantages of the traditional grid design and the automobile oriented neighbourhood, has generated considerable interest with related research ongoing at several Canadian universities, including the University of Guelph, the University of Toronto and the University of British Columbia (for example, see Hawkins (2007)).

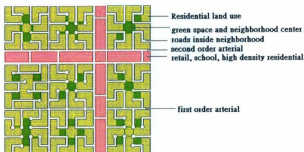


Figure 2.4: Example of a fused grid neighbourhood with twinned arterial
(Source: CMHC, 2004)

The fused grid design was developed by Fanis Grammenos and his colleagues at CMHC. It claims efficiency of land use and traffic flow, better quality of life and minimal environmental impact (CMHC, 2004). The design claims to combine the advantages of two North American planning traditions: the effectiveness of the grid network in pedestrian traffic and the automobile orientation found in super blocks and cul-de-sacs. The fused grid design claims to provide a balance between automobile and pedestrian movement, and to create safe, sociable streets and easy connectivity to community

facilities, while retaining efficiency in land use and infrastructure. The fused grid design is also said to be flexible, i.e. easy to adapt from existing street configuration.

A typical fused grid neighbourhood design is composed of half mile grids. Each grid contains four blocks, with first order roads separating the blocks. Grids are in turn separated by second and third order twinned arterials that provide moderate to high-speed one way traffic while at the same time allowing easy crossing for pedestrians. Inside blocks, crescents and cul-de-sacs are used to eliminate through traffic, while a continuous, open-space pedestrian path system provides better access to parks, public transit, and retail and community facilities. The most intensive land uses such as schools, retail and community facilities and high density residential uses are located between the parallel arterial roads.

Table 2.1 provides a summary of the characteristics of the four neighbourhood designs introduced in this section.

2.2 INFLUENCES OF NEIGHBOURHOOD FORMS

As described in Section 2.1, most neighbourhood forms are designed to either promote or discourage a certain mode of traffic: pedestrian or automobile. It is clear that traffic patterns will be different with different neighbourhood designs. Most existing research in this field focuses on how to quantitatively describe neighbourhood designs, and on how the aggregate traffic pattern is statistically linked to neighbourhood designs (Boarnet and Crane, 2001a).

Table 2.1: Comparison of neighbourhood designs

<i>Design</i>	<i>Time frame</i>	<i>Street network</i>	<i>Separation of land use</i>	<i>Pedestrian-friendly features</i>
Traditional Grid	Pre-1930	Grid	Integration of land uses	Short access distance to facilities
Post-war Suburban	1945-present	Large blocks, hierarchical street system, extensive use of loops, cul-de-sacs and curvilinear streets	Separation of residential land use from other land uses (loose integration of land uses featured in some later implementations)	Sidewalks provided on certain streets, pedestrian-only routes provided in some implementations
Neo-traditional development	1980-present	Grid-like network, T-intersections	Integration of land uses	Short access distance to facilities, sidewalks and pedestrian-only routes
Fused grid	Recently proposed	Large blocks and cul-de-sacs for automobiles, grid network in effect for pedestrian with the pedestrian-only routes system	High density residential and other land uses between twinned arterial	Short walking distance to facilities, sidewalks and pedestrian-only routes

As Batty (2003) points out, behaviour in human systems is determined not only by personal preferences, intentions and desires, but also “by the environment which reflects the spatial or geometric structure in which the agents function as well as variability between agents, in terms of their intrinsic differences and the uncertainty that they have to deal with in making any response”. In fact, it is widely accepted that there are direct relations between land use patterns, socio-economic characteristics and travel patterns

(Veldhuisen *et al.* 2000; Matt *et al.* 2005). For example, a UK study using multiple regression analysis on UK national survey data reveals that land use and socio-economic characteristics can explain up to 80% of total distance traveled by residents (Stead, 2001). The research shows that population density, settlement size and bus frequencies are closely related to travel distances. Research in Copenhagen reveals that distance to urban centers also has clear influence on travel distance (Næss, 2006). Research also shows that a balance of home and jobs (mixed land use) promotes shorter commutes to work (Levinson, 1998; Horner, 2002; Sultana, 2002; Cervero and Duncan, 2006), and that increased availability of local facilities increases the engagement in associated activities in these facilities (Lee *et al.* 2009).

Neighbourhood characteristics also influence mode choice, and recent research has discovered that mixed land use (Cervero and Duncan, 2003), improved street connectivity (Boarnet and Crane, 1998, 2001; Greenwald and Boarnet, 2000; Kitamura *et al.* 1997), sidewalk availability (Rodriguez and Joo, 2004), perception of safety and traffic (Estupinan and Rodriguez, 2008), and walking distance to local shopping area (Cao *et al.* 2006) all have an influence on the choice of walking/transit mode and the number of walking trips.

It is also recognized that there might be interactions between land use characteristics and socio-economic characteristics, which may have influenced the accuracy of statistical analyses (Stead, 2001). For example, research by Sen and Baht (2006) confirms that household location attributes and built environment characteristics

of the household residential neighbourhood are correlated with the type and use of automobiles.

The situation is further complicated by the existence of self-selection. People not only react differently to different neighbourhood forms, they also choose different neighbourhoods to live in based on their preferences. For example, it is believed that most people prefer living close to green space and water, so it might be expected that people who do not live close to green space will make more trips to remote green spaces. However, research shows that with the existence of self-selection, people who live close to green spaces are more likely to be "nature-lovers" and make more trips to remote green spaces than people who do not live close to green spaces (Maat and Vries, 2006). Understanding the role of self-selection is important in understanding the causal relationship between the built environment and travel behaviour (Handy *et al.* 2005). Some research shows that the observed associations between travel behaviour and neighbourhood characteristics can largely be explained by self-selection (Bagley and Mokhtarian, 2002), while other studies find that neighbourhood type does influence travel behaviour, even after attitudes are accounted for (Schwanen and Mokhtarian, 2005; Cao *et al.* 2006, 2009; Chatman, 2009).

Different traffic patterns further translate into differences in the patterns of daily life inside the neighbourhood. Different levels of pedestrian and automobile travel influence the chance of social interaction on the streets, pedestrian safety, local environment, the possibility of congestion on the roads and the health of local residents.

SOCIAL INTERACTION:

Increasing social interaction inside urban neighbourhoods is one of the major objectives of recent neighbourhood planning approaches. For example, new urbanism neighbourhoods are designed to “bring people of diverse ages, races, and incomes into daily interaction, strengthening the personal and civic bonds essential to an authentic community” (Charter of the New Urbanism (CNU), 2001). Urban streets are considered important social places in the planning world. The Geometric Design Guide for Canadian Roads by the Transportation Association of Canada (TAC) (1999) stated that: “Streets in an urban setting serve a variety of functions including provision for motorized vehicles, cyclists, and pedestrians, and the creation of public spaces for social interactions and contact”. Although it is debated whether neo-traditional development or other neighbourhood forms directly influence social interaction and the sense of community inside the urban neighbourhood, it is clear that neighbourhood design can encourage residents to use streets, and “provide opportunities for passive contacts, or unintentional encounters that present the opportunity for acknowledgement of another’s presence and a chance to discover the other’s nature through observation and conversation” (Grannis, 2005). The number of passive contacts is positively associated with the chance of social interaction (Grannis, 2005) which leads to at least “weak ties” among residents (Talen, 1999). Weak ties, weak as they sound, are responsible for the majority of the structure of social networks in society as well as the transmission of novel information through these networks. The face-to-face interaction is also good for building collective solidarity

among different population/social groups and eroding intergroup stereotype and prejudices (Garster and Boozar, 2007).

The social environment formed by social interaction in turn influences travel decisions. For example, research has confirmed that the frequency of unplanned interaction with neighbours is positively related to the frequency of walking (Lund, 2003). A San Francisco study showed that social cohesion and trust influence the number of walking trips to school for children (MacDonald, 2007). The pedestrian traffic on the roads also influences the route choices of other pedestrians. A California study found that 60% of pedestrians strongly agree or agree that the existence of "other people out walking" influence their route choice (Schlossberg *et al.* 2007)

PEDESTRIAN SAFETY:

Pedestrian safety can be interpreted as the possibility of pedestrian/automobile vehicle collisions. The US Bureau of Transportation Safety data show that most common types of pedestrian/automobile collision are crossing at an intersection (32%), mid-block crossing (26%) and walking along road (8%) (Stutts *et al.* 1996). Pedestrian/automobile collisions may also be the result of high speed and/or high volume automobile traffic, which makes crossing difficult and makes drivers unwilling to yield in certain situations (FHWA website). The Walking Security Index project (Wellar, 2009) calculates the walking security indices based on traffic volume, sidewalk and crosswalk quality, driver's behaviour and several other factors. A review by Southworth (2005) concluded that criteria that have been formulated for pedestrian safety include crossing times and length

of cross walks, traffic speeds, sidewalk width and condition, traffic controls and night lighting.

Pedestrian safety influences the choice of walking mode and the choice of route for pedestrians. Research shows that connected pedestrian paths (less crossing), availability of sidewalks and less volume of traffic all contribute to the choice of walking mode (Cao *et al.* 2006), and that safety is the second most important factor (only next to "shortest/fastest route") that influences pedestrian's route choice (Schlossberg *et al.* 2007)

POLLUTION AND PEDESTRIAN EXPOSURE TO POLLUTION:

The emission of greenhouse gases such as CO₂, NO_x, HC and other polluting gases, which is directly related to the consumption of carbon-based fuel, is regarded as one of the most serious threats to the environment through the greenhouse effect. Transport is the second largest source of greenhouse gas emission, and road transport accounts for 92% of the total emissions in the transport sector (Ericsson *et al.* 2006). Neighbourhood forms influence the amount of emission not only by changing the demand for road transport (thus the total distance traveled and total fuel used), but also by changing the characteristics of driving through different street patterns and traffic controls (thus changing the speed of travel, the number of stops and accelerations) (Frank *et al.* 2000; Brundell-Freij and Ericsson, 2005). Research shows that a car generates much more emissions at the acceleration stage than during cruising or idling (Frey *et al.* 2000). Thus, not only does the total distance traveled by automobiles matter, the number of short trips and the number of stops on route also has a great influence on the level of emissions.

Exposure to the pollutants also constitutes a health risk for pedestrians (Kaur *et al.* 2006), and a properly selected route may significantly reduce air pollution exposure (Hertel *et al.* 2008). Thus, automobile emissions have the feedback effect of changing pedestrian route and mode choice, as many pedestrians not only avoid busy traffic areas, they also avoid exposure to the emissions (Kaur *et al.* 2006).

CONGESTION:

Although the origin of traffic congestion is a complex process (Benenson and Torrens, 2004), it is clear that the major direct cause is too many cars on the road. Traffic congestion not only causes longer time spent on the road, it also has the effect of generating more emissions because of the stop and go nature of travel during periods of congestion (Frank and Engelke, 2005). Depending on the design of a neighbourhood, certain streets in the neighbourhood may have high traffic volume during morning and afternoon peak time which in turn is associated with the likelihood of traffic congestion.

Studies have also found a link between the level of congestion and the stress level of automobile drivers which can be further linked to the health of the drivers (Hennessy and Wiesenthal, 1999; Hennessy *et al.* 2000)

HEALTH:

Research on the relationship between neighbourhood form and health has been mainly focused on the influence of the neighbourhoods' socio-economic characteristics such as poverty rates and minority concentration on residents' health conditions (for

examples of such studies, see Pettit *et al.* 2003). Recently, a number of studies have begun to link the physical form of neighbourhoods with residents' health conditions. A US study in 2001 showed that neighbourhood characteristics, including the presence of sidewalks and enjoyable scenery, were positively associated with physical activity (Brownson *et al.* 2001), and regular physical activity is widely believed to confer important health benefits (Ainsworth *et al.* 2000). The Canadian Institute for Health Information (CIHI) recently reported the discovery of a link between a neighbourhood's physical form, residents' likelihood to perform physical activities and residents' likelihood of being overweight (CIHI, 2006).

The physical form of a neighbourhood not only changes the accessibility, and thus the use of facilities for physical activities, it also encourages or discourages walking, which is one of the most common and most accessible physical activities. In health research, the intensity of activities is measured with MET (metabolic equivalent). For example, moderate physical activity is defined as physical activity with a MET value of 3 to 6, while vigorous physical activity is defined as physical activity with a MET value of more than 6 (Ainsworth *et al.* 2000). Vigorous activity has traditionally been associated with improvements in health, but moderate physical activity has been shown to confer such benefits as well (Ainsworth *et al.* 2000; Eyster *et al.* 2003). According to the Compendium of Physical Activities (Ainsworth *et al.* 1993), walking on a firm surface with the speed of 2.5 miles per hour (mph) is a 3 METs physical activity, while walking on a firm surface with the speed of 3 mph (which is considered a moderate speed) is a 3.5 METs physical activity. The pedestrian speed defined in the U.S. Manual on Uniform

Traffic Control Devices (FHWA, 2003) is 1.2 metres per second, which can be translated into 2.7 mph. So, not only does brisk walking (with walking speed of 3.5 mph or more) have health benefits, but so too do normal walking activities such as walking to school, walking to work or walking to shopping.

Several other factors are also related to community health. As stated earlier, exposure to automobile emissions constitutes a health risk for pedestrians, and the level of congestion is related to the stress level of automobile drivers.

In summary, neighbourhood design, through the characteristics of street networks and location of houses and facilities, influences residents' accessibility. Together with local residents' socio-economic status and personal preferences, these factors jointly influence residents' mode and route choice which in turn leads to different patterns of social interaction opportunities, community health, pedestrian safety, pollution and congestion inside the neighbourhood. These outcome patterns, through feedback processes, in turn influence accessibility in the neighbourhood and mode/route choice behaviour of local residents. Figure 3.1 in Section 3.1 provides an overview of the above relationships.

2.3 MODELLING CITIES AND TRANSPORTATION SYSTEMS

2.3.1 URBAN MODELLING

For more than 100 years after von Thünen published his land use theory in 1826, until the 1950s, location theories that describe an optimal and steady-state city structure dominated urban studies, with the most influential theory being Alonso's decaying-with-distance land rent theories (Fujita *et al.* 1999; Benenson and Torrens, 2004). Alonso's bid rent theory can be seen as an extension of the von Thünen theory from rural to urban land use, and both theories describe an optimal and steady concentric land use structure around a single centre. Many urban components such as population, jobs, services and transport networks remain beyond the framework of these models.

In the 1950s and 1960s, equation-based models were widely used to model dynamics in the city. Gravity equations were widely used in these models to simulate the distribution and flow of population and industries inside urban areas (Torrens, 2000). Major problems with these comprehensive urban models are that they are aggregated (thus lack details), equilibrium oriented (lack understanding of how a city changes) and black-boxed (with "mechanisms that even the model-builders might not perceive or distinguish" (Benenson and Torrens, 2004)).

With advances in system theory and complexity theory, it is now recognized that cities are intrinsically complex systems which, differing from simple systems, exhibit properties that are beyond convergence to a globally stable equilibrium, properties such as creativity, emergence and other non-equilibrium phenomena (Benenson and Torrens, 2004). As von Bertalanffy points out: "Concepts and models of equilibrium, homeostasis, adjustment, etc., are suitable for the maintenance of the system, but (turned out to be) inadequate for phenomena of change, differentiation, evolution, negentropy, production

of improbable state, creativity, emergence, *etc.*" (von Bertalanffy, 1968, cited in Benenson and Torrens, 2004). In other words, traditional mathematical and statistical analysis is not enough to analyze and predict the dynamics of complex systems like cities.

In light of the problem, new techniques and methods were needed. It was found that in a complex system, system properties result from collective local interactions of the constituting parts - heterogeneous actors - and emergence assumes a recognizable, limited set of atomic rules that are applied at local (individual) levels among a large number of heterogeneous entities (Benenson and Torrens, 2004). Thus, Cellular Automata (CA) and Multi-Agent Systems (MAS) which use simple rules applied to a population of cells or agents to generate complex system behaviour are intrinsically suitable for modelling complex systems.

CA are defined as cells in a cell space that change their states over time based on rules concerning both the states of the cells themselves and the states of their neighbourhoods. An MAS is composed of a community of agents situated in an environment, with agents perceiving and acting upon their environment based on internal rules and internal/external information. Agents can be used to model human-like behavioural processes such as problem solving, planning, decision-making and learning activities. CA and MAS also make possible the generation of structure from the bottom up (which is important for individual-based urban and transportation simulation) rather than assigning activities from top down.

CA and Agent-Based Modelling (ABM) techniques have been widely used in many academic fields including Ecology (Grimm, 1999), Sociology (Gilbert and Conte, 1995; Rindt *et al.* 2002) and Geography (Benenson and Torrens, 2004; Parker *et al.* 2008). They are found to be ideal for modelling urban phenomena, as cities can be easily interpreted as a composition of cells (land lots) with agents (people, enterprises and organizations) interacting with each other or moving around in the space. The increasing availability of fine scale data, modelling platforms and code libraries for CA/ABM and increasing computing power of modern computers also make CA/ABM simulations at higher resolutions feasible.

The use of CA in geography originates from the raster conceptualization of space in the late 1950s. Several models in the 1950s and 1960s utilized a cell space with dynamically changing cell states, though no neighbourhood effect was included (Benenson and Torrens, 2004). It was not until the 1990s when true CA models began to be widely used in large scale land use change and urban sprawl simulations (White and Engelen, 1993; White *et al.* 1997; Li and Yeh, 2000; Cheng and Masser, 2004).

Compared to CA models, agent-based models are widely used in finer scale simulations focusing on location dynamics of households (Portugali *et al.* 1997; Portugali, 2000), automobiles (Benenson *et al.* 2008) and pedestrians (Helbing *et al.* 2000; Batty, 2003; Lee and Lam, 2008). Though it is believed that nearly all agent-based models can be implemented in the form of CA (Benenson and Torrens, 2004), agent-based models are often used in the simulation of complex systems that involve movement

patterns of agents and spatial interactions between agents, as it is more "intuitive" to interpret such systems as agent-based models where agents interact in an environment.

2.3.2 TRANSPORTATION MODELLING

Like urban modelling in general, transportation modelling traditionally relied heavily on aggregate analysis as well. A common approach is to divide the process into four steps: trip generation, trip distribution, mode choice and route assignment (Banister, 2002). Network flow models and regression models are widely used in this field. In a network flow model, traffic flow between different traffic zones are calculated as function of the characteristics of respective zones, such as population or activity opportunities. The gravity equation, which predicts the attractiveness of a region based on its relative population or activity opportunities, is widely used in network flow models (Torrens, 2000). Regression models, which predict trips based on existing trip data and regression analysis, are also widely used.

A trip is in essence a series of human decisions. The time, purpose, destination, mode and route of a trip all involve human decisions. Different approaches, including utility-based, activity-based and constraint-based approaches, have been used to study and simulate the decision behaviour. The utility-based approach is used in the comparison of different destinations or travel modes based on a cost/benefit analysis (Timmermans, 2003). The activity-based approach puts travel demand into a finer time scale, with

people optimizing their entire activity pattern rather than maximizing utility for separate trips (Veldhuisen *et al.* 2000). Constraint-based approaches put time and economic constraints into decision making, so that the result would closely follow reality.

A general problem with traditional transportation models is that they rely heavily on aggregate analysis (Veldhuisen *et al.* 2005, Estupinan and Rodriguez, 2008). Not only do they ignore personal intentions and preferences, the influence of the environment is also rarely considered.

Like cities, transportation systems are also complex systems. Transportation systems are the outcome of human decisions, and ABM provides an intuitive and easy way to include personal intentions and preferences in transportation modelling. In such a model, individual persons, including drivers, transit passengers and pedestrians, can be seen as agents that move around the transportation network, making decisions from time to time based on personal characteristics and preferences and information obtained from the environment. Initial attempts in this field focused on how collective phenomena such as traffic jams and detours are formed in the system (Benenson and Torrens, 2004). Real-world applications appeared in the early 1980s with the appearance of the first MAS traffic simulation systems such as MULTSIM (Gipps, 1986). Complex driver behaviour such as lane changing and way finding, and various transportation network characteristics such as intersections, stop lines and signal timings are explored in this system. Currently, research in this field can be classified into two approaches. Most of the agent-based transportation models, including the famous TRANSIMS application developed at Los Alamos National Laboratory (Smith *et al.* 1995), use computer generated population on a

real-world road network, and results are compared to characteristics of car traffic in the real world. Many newer studies in this field focus on obtaining real-time traffic information from vehicular networks (networks formed by vehicles which wirelessly interact with each other on the road) (Lee *et al.* 2009), and studying the influence of real-time information on travel behaviour and traffic patterns (Dia, 2002; Wahle *et al.* 2002). As discussed above, in terms of scale, initial simulations focus on the microscopic phenomena such as local traffic patterns influenced by traffic signals and car-following/lane-changing behaviour, while many recent studies begin to focus on the traffic patterns at the national or regional level (Raney *et al.* 2003) and on the integration of micro-level automobile traffic simulation with regional-level simulation (Smith *et al.* 1995; Grangier, 2006).

On the pedestrian side, agent-based research has been ongoing since the 1970s. Compared to car traffic, pedestrian movement is more flexible, and thus more difficult to simulate. Most of the research in this field focuses on pedestrian movement in constrained environments such as narrow passages (Helbing *et al.* 2000), building floors (Batty, 2003), subway stations (Castle, 2006) and pedestrian-only streets (Schelhorn *et al.* 1999; Batty *et al.* 2003). Also, most of these studies are aimed at dealing with emergency situations such as evacuating rooms and controlling crowds in the streets.

With existing research focusing on either trip and traffic patterns at the metropolitan/regional scale, or micro-level movement patterns of automobiles and pedestrians, the dynamics at the neighbourhood-level are often neglected. The simulation and studying of neighbourhood-level trip and traffic pattern will contribute to the

metropolitan-level models with local dynamics, while provide input and constraints to the micro-level movement models of automobiles and pedestrians.

The treatment of urban neighbourhoods as complex systems will contribute to the study and comparison of neighbourhood designs. Existing studies on neighbourhood designs mostly focused on building integrated models that are based on aggregate travel behaviour (McNally and Ryan, 1992; Stone *et al.* 1992; Crane, 1995). The complex nature of the urban neighbourhoods means that an agent-based model will be able to better represent the outcome of the system, as well as the internal dynamics associated with the system. An integrate agent-based model that combines land use characteristics and transportation networks, that includes automobile driver, transit passenger and pedestrian agents, that considers personal preferences and choices, and that focuses on the neighbourhood scale has not been seen in the literature. In such a model, patterns of pedestrian and automobile movement, as well as how different neighbourhood forms influence these movement patterns, can be observed and analyzed.

CHAPTER 3: METHODOLOGY

Agent-based modelling techniques are employed in this study to explore the relationship between neighbourhood forms and traffic patterns inside urban neighbourhoods. This chapter gives an introduction to the study, and explains the underlying methodologies.

3.1 STUDY OVERVIEW

Various studies have suggested that individuals decide their activity pattern partly in response to neighbourhood forms (Batty, 2003; Cervero and Duncan, 2003; Rodriguez and Joo, 2004; Cao *et al.* 2006). For an individual in the city, the activity pattern is shaped by travel needs, personal preference and time and economic constraints. For example, a student needs to go to school every school day, a worker needs to go to work every workday, one or more persons in a household needs to go shopping once in a week, and may choose to watch a movie occasionally, and people may want to visit their friends once in a while. People have different preferences which affect their travel decisions. For example, some people may prefer shopping at nearby stores while other people prefer shopping centers that may be at a distance. For a given distance, some people may prefer to walk while other people prefer to drive. And some people may prefer a specific route so that they can avoid crossings, roads without sidewalks or roads with busy traffic. Travel decisions are also shaped by time and economic constraints, including the

availability of free time, the possession of a driver's license and the availability of an automobile.

It is expected that neighbourhood configuration influences travel behaviour in three different ways: First, it directly determines the route network, and thus establishes the possible route choices and determines the characteristics of the chosen routes for pedestrians and automobiles. Second, it influences the accessibility to public transit and other facilities, and thus affects modal split. And third, it determines the availability of activity opportunities inside the neighbourhood, thus affecting the distribution of activities inside and outside the neighbourhood.

These characteristics in neighbourhood configuration and subsequent impacts on travel behaviour will affect many aspects of life in urban neighbourhoods (Figure 3.1). For example, some neighbourhood configurations may be associated with relatively higher levels of pedestrian travel and lower percentage of automobile travel. More pedestrian travel means more social interaction opportunities on the street. More pedestrian travel is also associated with a lower likelihood of overweight, obesity, and other related health problems. Also, for the pedestrians on the street, different street layout and road conditions lead to differences in-street safety levels, because street layout and road conditions decide the number of crossings, the availability of sidewalks and the width of roads which influences the risk of crossing the roads; this will further affect the choice of route or the mode of travel. On the other hand, some neighbourhood configurations may be linked to higher level of automobile traffic on certain roads, and

this means a higher level of pollution, higher level of pedestrian exposure to automobile emissions and greater chance of congestion.

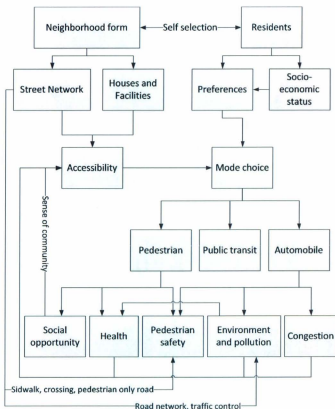


Figure 3.1: Influences of neighbourhood design

These phenomena will be researched in this study. More specifically, this study is designed to find out how different neighbourhood designs influence travel behaviour, traffic patterns, pedestrian safety, social interaction opportunities, residents' health and the environment inside the neighbourhood. A list of outcome measures can be found in Table 3.1.

Table 3.1: List of outcome measures

<i>Outcome measures of the study</i>	
Travel and traffic patterns	Travel behaviour (trip length, modal split, trips by type and by demographic group)
	Traffic pattern and possibility of congestion
Daily life	Pedestrian safety (represented by the number of crossings, availability of sidewalks and pedestrian-only routes, and street traffic conditions)
	Social interaction opportunities
Environment and health	Emissions (Vehicle distance traveled inside the neighbourhood, characteristics of automobile travel which link to emissions)
	Total distance travelled by pedestrians, and pedestrian exposure to automobile emissions

In general, the research problem concerns a group of individuals (agents) acting and interacting inside the neighbourhood (map), with the objective being observing and studying the patterns of outcome. Based on the nature of the problem, an agent-based model is proposed. In land use and transportation studies, an agent-based model normally contains a base map which represents the study area, as well as a population of agents

which represents individual persons in the study area. In this study, the base map represents a neighbourhood in the study area, and agents represent all the local residents of the area. The model simulates the travel behaviour of local residents during a 24-hour period. Each agent in the model has its own schedule, and moves on the map according to the schedule. The route and transportation mode of each trip are influenced by both road network characteristics (such as the availability of sidewalks and pedestrian-only routes, and traffic level on the roads) and personal characteristics (such as socio-economic status and personal preferences).

In a simulation run, the model reads the map (which contains information regarding the location and characteristics of residential houses, work/school/shopping/service/transit facilities and road networks), and generates the agent population based on survey data. The model then allocates the agents (grouped by households) on the map, and assigns an origin and a destination to each trip of each agent. For trips ending inside the neighbourhood, the destination could either be a local facility or a local house depending on the trip purpose. For trips ending outside the neighbourhood, the destination is set to be an exit point of the neighbourhood, since the simulation only covers the area inside the neighbourhood. The route of each trip is calculated based on a customized shortest route function which takes road characteristics and traffic conditions into consideration. The mode of each trip is decided based on the utility of each mode (which is in turn calculated based on time, cost, safety and health measures). In the model, pedestrian agents avoid automobile traffic, while they are attracted to pedestrian traffic, with a "spin-up" process used to stabilize model output.

Measures listed in Table 3.1 are collected as results, which are then used to analyze the influence of neighbourhood forms and configuration.

The simulation model is calibrated based on detailed travel logs from seven Traffic Analysis Zones (TAZs) and aggregated trip data from 40 TAZs in Ottawa, Ontario. After the calibration, experiments are carried out on seven hypothetical neighbourhood configurations representing the four neighbourhood types discussed in Section 2.1 (traditional grid, post-war suburban, neo-traditional neighbourhood and fused grid design), as well as three neighbourhood configurations for the Barrhaven region of Ottawa. A detailed description of the simulation software and the data flow is presented in Chapter 4, while the formulation and calibration of the model are presented in Chapters 5 and 6.

3.2 AGENTS

3.2.1 CHOICE BEHAVIOUR

Agents are of course the most important part of an agent-based model. In this study, agents represent local residents and incoming visitors who make decisions on route and mode choice. As discussed in Section 2.3.2, different approaches, including utility-based, activity-based and constraint-based approaches, have been used in transportation simulations. This study tries to combine the advantages of each of the three approaches.

The utility-based approach, or random utility model, has been widely used in transportation research. The basic assumption of a random utility model is that an individual will settle on one decision from a set of available options so that the most utility is gained (Torrens, 2000). Utility is the trade-off between the benefits (the positive part of utility) and the costs (the negative part of utility, often called "disutility"). The notion of "disutility" is widely used in transportation studies (Recker, 1994; Kockelman, 1998; Hoogendoorn and Bovy, 2004), probably due to the fact that cost measures such as time and cost can be more easily identified and mathematically calculated than benefit measures. It is also argued that disutility is a form of accessibility measured in the transportation system (Geurs and Wee, 2004). While many different measurements of accessibility have been used in transportation studies (for example, see Liu and Zhu, 2004; Geurs *et al.* 2006), utility-based accessibility, combining an individual's spatial-temporal constraints and feedback mechanisms between accessibility, land use and travel behaviour, is seen as the future of accessibility studies (Geurs and Wee, 2004, Liu and Zhu, 2004).

Time and cost are the most commonly used disutility items, but many other factors influence mode and route choice behaviour as well (Matt *et al.* 2005). For example, street safety and automobile pollution emission would discourage people from choosing certain routes or even abandoning the walking mode altogether (Bhat *et al.* 2009; King *et al.* 2009). Measures considered in this study include availability of sidewalks and pedestrian-only routes, number of road crossings needed for pedestrians, automobile traffic level along the pedestrian routes which influences both pedestrian

safety and pedestrian exposure to automobile emission, and pedestrian traffic level which influences the chance of social interaction. The intention is that these factors, along with the stochastic influence introduced into the model (see Section 3.4.2), will explain the travel decision factors other than time and cost. With time, cost and safety measures, the utility function is often written as:

$$U = \alpha T + \beta C + \gamma S$$

where U refers to the (dis-)utility of the trip, with T , C , S refer to time, cost and safety measures respectively. α , β and γ are weighting parameters.

For each trip (or each round trip, a series of trips with the first trip starting at home and the last trip ending at home) and each option for route and mode, the disutility is calculated as a weighted total of time, cost and other disutility measures. The probability of choosing a certain option is then calculated based on a variation of McFadden's logit model. For example, for a set of three options, the probability of choosing option 1 is calculated as:

$$P_{option} = \frac{e^{rU_{option}}}{e^{rU_{option}} + e^{rU_{option2}} + e^{rU_{option3}}}$$

where r is a parameter that determines the probability of choosing the mode with the greatest utility (or the least dis-utility); as r becomes large, this probability approaches one, and probabilities of choosing the other options approach zero, while for $r=0$, all modes have an equal probability of being chosen regardless of their utility values.

A traditional non-hierarchical logit formulation suffers from some weaknesses. For example, the logit framework assumes that individuals evaluate every available alternative before settling on an optimal one (Torrens, 2000). In reality, because of constraints such as time and economic status, individuals often settle on a subset of the available options. For example, the selection of driving would require the availability of a car and the possession of a driver's license. In this study, such constraints are evaluated in the mode choice process (see Section 6.1 for details).

Time is not only a (dis)utility, it is also a constraint. For example, when family members share the use of a car or several cars, they must decide who or which trip has the priority for the use of the car(s). For an individual, trips such as work and school trips are inelastic (Næss, 2005). Not only is the demand not influenced by neighbourhood design, the timing of these trips is often fixed. But other trips like shopping and social trips are elastic in that their time and duration can be changed to a certain degree. In deciding the mode of trips, not only should the individual consider the schedule of a whole day or at least a whole round trip, he/she also should consider the demand and schedule of other family members. The solution is an activity-based approach, with the family as the unit for activity and car use planning. This kind of mechanism has been used in other transportation simulations (for example, see Bowman and Ben-Akiva, 1996; Arentze and Timmermans, 2004).

Utility is subjective (Hoogendoorn and Bovy, 2004). The so-called "taste variation" means that, even with the same amount of time and cost spent on a trip, or with the same amount of traffic on the road, different individuals will have different

perceptions and different responses. Socio-economic status and personal preference affect the perception of utility. It is suggested that utility perception in a population follows a normal distribution, with most people having similar perceptions while a few people show extreme attitudes. The use of the normal distribution to represent taste variation is common in transportation studies (for example, see Hess *et al.* 2007; Ettema *et al.* 2007; Takama and Preston, 2008). Assuming that χ is a normally distributed variable:

$$\chi = N(\mu, \sigma^2)$$

with the consideration of taste variation, the utility function can be rewritten as:

$$U = \alpha\chi_i T + \beta\chi_i C + \gamma\chi_i S$$

where μ and σ refer to the mean and standard deviation of the taste variation values.

However, in practice, it is difficult to calculate and determine the characteristics such as the mean value and the standard deviation of the distribution. A randomly assigned taste variation value can also lead to calibration problem, especially in an individual-based model, since the random value may not reflect the true taste value of the corresponding agent. A solution is to parameterise the time, cost and safety coefficients of the utility equation using socio-economic characteristics of the agents. With such parameterisation, the utility function can be rewritten as:

$$U = (\alpha_0 + \sum_i \alpha_i E_i)T + (\beta_0 + \sum_i \beta_i E_i)C + (\gamma_0 + \sum_i \gamma_i E_i)S$$

where E refers to the set of socio-economic variables considered in the model.

Thus, given the characteristics of the individual, different “tastes” can be generated in a deterministic manner. This parameterisation allows incorporating of taste heterogeneity in an economical way (Ortuzar and Willumsen, 2001). This technique was proposed by Fowkes and Wardman (1988) and has been used in a few other studies (for example, see Rizzi and Ortuzar, 2003). The use of this technique will be further discussed in Sections 6.3 and 6.4.

3.2.2 POPULATION SYNTHESIS

It is nearly impossible to obtain individual level population data for every resident in a neighbourhood or study area. In transportation studies, it is common practice to generate a synthetic population from survey data which represents a certain percentage of the population in the area. Population synthesis is even more important to agent-based models as it resolves many problems with the use of aggregate data, and it helps get the maximum value out of the available data. For example, average commute time is often considered as an important indication of transportation network efficiency. An increase in average commute time seems to mean heavy traffic and more congestion. However, it could also be the result of more long-distance and uncongested commutes. Such examples reveal the inadequacy of aggregate data in complex situations (Benenson and Torrens, 2004). The use of synthetic data can help reveal patterns, characteristics or problems at the individual level or very small scale.

Synthetic populations have been used in microsimulations since the 1950s. One of the initial uses of synthetic population can be traced to Guy Orcutt who used a synthetic population in his microsimulation model of household behaviour under different social policies (see Orcutt *et al.* 1976). In transportation simulation, Greig Harvey's STEP model built in 1978 used a synthetic population for a simulation of the San Francisco Bay Area (Harvey, 1978). One of the most famous transportation simulation models, TRANSIMS, also uses a synthetic population (Smith *et al.* 1995).

Transportation studies, especially in the United States, have widely used the Iterative Proportional Fitting (IPF) method to build synthetic populations. The main reason is that in the United States, samples of individual level census data are made available at the scale of the Public Use Microdata Area (PUMA), which is usually an area with more than 100,000 persons, while transportation simulation often needs to be carried out at smaller scales like census blocks, where only aggregate data are available. Thus, individual data must be synthesized so that they replicate the PUMA data while also fitting the aggregate characteristics of the census block. For a description of the IPF method, see Wong (1992).

An IPF based synthesis method has been programmed for this study. However, the survey data used in this study are originally from the neighbourhood level and no IPF transformation is needed. Instead, the expansion factors contained in the data, which are calculated based on the proportional difference between survey data and census data, are used to obtain the entire population. This method has also been used in other studies (for example, see National Cooperative Highway Research Program (NCHRP), 2005).

It has been shown that many trip characteristics, such as trip rate per person and trip distance, follow the gamma distribution (Zhang and Mohammadian, 2008). This provides an approach to examining the output of population synthesis (see Section 5.2.4 for details).

3.3 THE ENVIRONMENT

Agents live in an environment. For a map-based model, a Geographic Information System (GIS) provides an intuitive way to present the environment.

The proposed model does not contain a land use change module. Instead, land use changes are manually manipulated through the GIS map and database, and are then instantaneously provided to the trip processing part of the model. Using an instantaneous link to join land use and transportation is one of the two major methods to build integrated models, with the other type being to link land use and transportation with a time-lagged link, so that feedback can occur between land use change and changes in transportation systems (Torrens, 2000).

One of the main focuses of this study is on the benefits of neighbourhood designs on pedestrians. Thus, the proposed model focuses on the neighbourhood characteristics that are most important to pedestrians, including sidewalks, pedestrian-only routes and pedestrian crossings. While automobiles only run on the right – or left, depending on the country – side of the road, pedestrians can walk on both sides of the road. The number of

road crossing for pedestrians clearly depends on which side of each street the pedestrian will choose. Pedestrians may also need to be on the same side of the street for potential social interactions to happen. These phenomena cannot be captured by the traditional use of GIS road map which represents a road as a simple line. In this study, the problem is solved using a creative use of the network map (see Sections 4.2.1 and 4.2.2 for examples of GIS and network map). In a network map, each intersection is represented as a "node", and each road is represented as two "edges" between two nodes with opposite directions. While directed edges are normally used to interpret directions of traffic, in this study they are interpreted as sides of roads. Thus, pedestrian traffic can be assigned to one of the two opposite edges representing one of the two sides of the road.

An important link between the environment and the agents' choice behaviour is the shortest path algorithm, which determines agents' route and mode of choice. The shortest path algorithm is an important area of study in transportation studies, and different methods and algorithms have been proposed and used in previous studies. Examples include: Swarm Intelligence (SI) (Batty *et al.* 2003), Learning Agents (Zhang and Levinson, 2004) and Dijkstra's algorithm (Dijkstra, 1959). In an SI method, a number of agents move out randomly to search for the destination. The agents who discover the destination would move back to the origin and lay trails so that other agents who have not discovered the destination can learn about the discovery. In a Learning Agents method, an agent moves along the network. At each node in the network, the agent tells the node about the agent's path and learns from the node about the paths taken by previous agents. A shortest path can then be discovered by repetitive comparisons and feedback between

the nodes and the agents. Dijkstra's algorithm is a mathematical algorithm that solves the single-source shortest path problem for a directed graph (*i.e.* a graph with directed edges between linked nodes) with non-negative edge weights. As road distance is always non-negative, Dijkstra's algorithm is naturally suitable for transportation simulations. While all the above methods are efficient, there is no comparison of the methods to date. In this study a shortest path algorithm based on Dijkstra's algorithm is used because the method is the most commonly used shortest path algorithm, it is reasonably fast, and it is adaptable and modifiable to the study's requirements. The length of each street section can be weighted to reflect the influence of traffic, sidewalk, pedestrian-only routes, road crossings and personal preferences ("tastes"). The result can be further randomized to reflect the nature of the agents' imperfect knowledge of the roads and road traffic conditions. These customizations make it possible to generate dynamic route and mode choice.

3.4 COMPLEX SYSTEMS

Agents, the environment, and corresponding rules form a complex system. As with all complex systems, feedbacks and uncertainties are important for the emergence, bifurcation and other phenomena of the system. In this study, the inclusion of feedbacks and uncertainties are essential to the generation of realistic trip and traffic patterns. An urban neighbourhood is a complex system that is constrained by spatial, environmental and technological factors. The behaviour of the individual agents is also bounded by

social and economic constraints such as social values and cost considerations. Thus, a model of such a system tends to produce stable output patterns. However, typical complex system behaviour can still be observed in the model. For example, in the proposed model, as pedestrian agents are attracted to other pedestrian agents on the roads, the random route selection of a pedestrian agent may increase the desirability of a certain street, and lead to the utilization of the same street by other pedestrians. While the modal split pattern produced by the model is normally stable, for the parameters of the model, especially the ones that control the influence of automobile and pedestrian traffic, there exists a certain range of parameter values where a street may become unrealistically attractive to pedestrians due to the positive feedback process, causing an unrealistically high number of pedestrians walking through the road and ultimately causing the pedestrian mode dominating the three mode choices. This extreme example illustrates the emergence, bifurcation and path-dependency features of the urban neighbourhood as a complex system.

3.4.1 FEEDBACKS

Feedback is important to a complex system. Feedback is crucial to simulating dynamic behaviour, capturing features that don't emerge from hierarchical models. Feedback has been studied in many urban and transportation studies (Bovy and Stern, 1990; Batty, 2001; Teknomo and Gerilla, 2005). It is argued that weak positive feedback is necessary to persistent structures and growth of the system (Batty, 2001). Feedback

processes in this study include the following: The sight of pedestrians on the road encourages agents to choose walking and to choose a certain route, while too many cars on the road discourages walking and discourages the use of the roads with high automobile traffic volume.

Positive feedback also leads to path dependency (Manson, 2007). In this study, the spin-up process (see Section 4.2.4) can be interpreted as the process in which agents learn the environment (road and traffic condition), and react to choose new route and mode, which in turn changes the environment (traffic condition), and so the feedback goes on. A limitation of the current model is that there is no direct feedback between human agents and the physical environment (*i.e.* physical condition of roads and characteristics of land use).

3.4.2 UNCERTAINTIES

Uncertainties are important to the modelling of complex systems. In an agent-based model of a complex system, uncertainties often come from probabilistic elements, both from random variations in exogenous factors and from the stochastic nature of endogenous processes (Veldhuisen, 2000). Uncertainties considered in this study include the uncertainties in agents' decisions and the uncertainties intrinsic to the model. In decision processes, agents have limited and imperfect information about road and traffic conditions, and often cannot make optimal decisions. For the model itself, while a model

is built to capture the characteristics of the real world, the model is required to be simple enough to be practical. Simplicity means selective inclusion and exclusion of factors, which means that there are uncertainties that are not captured by the model, or that the model may not be able to capture all the dynamics of the system.

A common practice in complex system modelling is to incorporate random variable(s) which represents uncertainties in the model (for example, see White and Engelen, 1993; Alexandridis and Pijanowski, 2002). The mathematical nature of random number generators means that repeatable results can be produced when using fixed "seeds", while system dynamics can be observed using different seeds. This repeatable behaviour is essential for the calibration and analysis of a complex system model. Randomization is essential to the generation of realistic traffic pattern in this study. Further discussion will be provided in Section 6.6.

CHAPTER 4: THE SIMULATION SOFTWARE

Based on the requirements of this study, a simulation program is developed based on the Repast simulation platform (version 3.1) and the OpenMap GIS mapping platform (version 4.6.5). This chapter describes the building process of the simulation software MIND (Modelling the Influence of Neighbourhood Design), including the selection of simulation platform (Section 4.1.1), comparison of the use of raster maps (Section 4.1.2) or vector maps (Section 4.1.3), as well as the performance tuning of the software (Section 4.1.4). The chapter also provides an introduction to the components of the software (Section 4.2.1 to 4.2.3), as well as the data flow between the components (Section 4.2.4).

4.1 BUILDING THE MODELLING SOFTWARE

4.1.1 SIMULATION PLATFORM

With the increasing popularity of agent-based modelling in Geography and other academic fields, software platforms for agent-based modelling are now widely available. There are currently more than 20 different platforms to choose from (Tobias and Hofmann, 2004; Swarmwiki website; Tesfatsion website). With a focus on free and open source software, proprietary software platforms were excluded at the beginning of the selection process. After extensive research into documents and examples of the remaining

software platforms, seven platforms were selected for comparison: SeSAM, NetLogo, StarLogo, Swarm, Repast, MASON and Madkit.

Comparisons were made in the following areas: difficulty level of programming and building an ABM model, customizability of the platform to specific requirements of this study, extensibility of the platform, speed of simulation and supported map and data formats. The popularity of a platform, and whether the platform is regularly updated, were also considered, because these factors influence the user base of the platforms and thus the level of support that might be expected during the software building and testing process.

Repast, or the REcursive Porous Agent Simulation Toolkit (Repast Organization for Architecture and Development, 2003), was selected for this study based on the fact that it is regularly updated, has a large user base, has extensive modelling libraries and programming APIs, is relatively fast and can be easily linked with GIS maps and population databases. Of the other six platforms, NetLogo and StarLogo are easy to use, but lack customizability; model building in SeSAM is based on a Graphic User Interface (GUI), not a programming language, which is extremely inefficient when dealing with a model that has a large number of agents and processes; Swarm is considerably slower than other platforms in model execution speeds (also see Railsback et al. 2006); MASON and MadKit both lack the level of GIS support in Repast. Table 4.1 provides a comparison of these seven platforms.

Table 4.1: Comparison of simulation platforms

<i>Name</i>	SeSAM	NetLogo	StarLogo	Swarm	Repast	MASON	Modkit
<i>Relationship</i>	/	Logo Family	Logo Family	/	Based on Swarm	/	/
<i>Based language</i>	Java	Java	Java	Java, Objective C	Java	Java	Java
<i>Model building language</i>	Not needed	Logo	Logo	Java, Objective C	Java, Python, C#	Java	Java, Python, Scheme, Jess, BeanShell, C/C++
<i>Programming difficulties</i>	/	Easy	Easy	Moderate	Moderate	Moderate	Moderate
<i>Agent definition</i>	By GUI, inefficient	Logo language	Logo language	By programming	By programming	By programming	By GUI, inefficient
<i>Extensibility</i>	Limited	Very limited	Very limited	Extensive code library	Extensive code library	Limited	Limited
<i>Popularity</i>		Very popular		Popular	Very popular		
<i>Map compatibility</i>	Special drawing tools	Drawing tools	Drawing tools	Import maps	Import maps	Import maps	Import maps
<i>Speed</i>	Moderate	Moderate	Slow	Fast	Fast	Slow	Fast
<i>GIS support</i>	/	/	/	ArcGIS	ArcGIS, OpenMap	/	/

Note: Table 4.1 represents an evaluation of the simulation platforms as of 2006 used for a specific test model.

Repast is now one of the most popular multi-agent simulation platforms and is frequently used in urban and transportation simulations. Repast is free and open source, and comes with libraries which provide support for basic simulation needs as well as GIS integration. Since it is based on Java, models based on Repast can easily use other Java packages and libraries to extend their functionality. The GIS compatibility of Repast is provided by OpenMap (OpenMap, 2005), which is free and open source as well. OpenMap can handle and process GIS maps and data in most popular formats like ArcGIS shapefile and MapInfo map files.

4.1.2 THE RASTER PROTOTYPE

In GIS, maps can be represented in two forms: raster or vector. A raster map consists of raster cells, which makes it ideal for use in CA models as well as ABM models. For example, for the purpose of this study, counting nearby agents (with whom chance of social interaction exists) can be easily done by counting the number of agents in the same cell or in the neighbouring cells.

Two prototype models are made using raster maps. The first prototype model was built with a Portable Gray Map (PGM). PGM maps are widely used in land use models. The file format is simple and is designed to be easily processed by software models. On the PGM map, each agent is assigned a home cell and a destination cell, and agents move between cells as they travel. Figure 4.1 shows an example of a PGM map file (left) and the network map generated based on the PGM file (right). The prototype model was able

to fulfill most requirements of the proposed model. Along with the building of the prototype model, it was also found that the shortest path algorithm that comes with Repast (version 3.1) was unable to produce shortest path under certain circumstances. A customized procedure was then programmed for the calculation of shortest path.

```
ncols 10
nrows 10
xllcorner 306160.0
yllcorner 9973000.0
cellsize 50
NODATA_value -9999
6 6 6 6 6 6 6 6 6 6
6 1 1 6 1 1 6 1 1 6
6 1 1 6 1 1 6 1 1 6
6 6 6 1 6 6 6 6 6 6
6 1 1 6 1 1 6 1 1 6
6 1 1 6 1 1 6 1 1 6
6 6 6 6 6 6 1 6 6 6
6 1 1 6 1 1 6 1 1 6
6 1 1 6 1 1 6 1 1 6
6 6 6 6 6 6 6 6 6 6
```

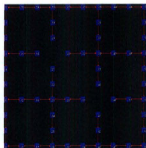


Figure 4.1: Example of a PGM file and the network generated from the file
(Left: content of a PGM file; right: the network generated based on the PMG file)

With the success of the first prototype, a second prototype model was created. The model used a raster map of the Barrhaven region in Ottawa. While the model still acted as expected, it turned out to be extremely slow. The problem is that, with a raster map, each road cell is considered a node in the road network. As there are thousands of nodes in the network, and the calculation time of shortest path increases exponentially with the number of nodes in the network, the model becomes extremely slow for a larger map. Figure 4.2 shows agents moving on the network in the second prototype model.



Figure 4.2: Example of a raster map based model with agents moving on the roads

4.1.3 THE VECTOR MODEL

The solution to the performance problem is to use vector maps. Different from a raster map, a vector map uses points, lines and polygons to represent map objects like intersections, roads and regions (Figure 4.3). A network map can be generated by identifying intersections, of which there are often less than 200 in a neighbourhood, thus making shortest route calculation much faster. Other advantages of using vector maps include the following: households can be allocated to different streets and street segments with different densities, and streets can have different characteristics such as sidewalk

availability or pedestrian-only status. Traffic characteristics can also be integrated as properties of streets. While this change requires more complex programming, it brings much improved performance, the flexibility of using GIS maps directly, and an intuitive user interface.



Figure 4.3: A GIS map in the vector based model

4.1.4 PERFORMANCE TUNING

With the vector map, the execution speed of the software was greatly improved. For example, the execution time of iteration through 5,000 agents (to move them on the map) shortened from 5 seconds to 0.3 seconds. But the vector map based software still

faced other performance issues, with the main issue being slow input/output (I/O) performance.

I/O issues existed in two situations: first, when the software imports population data from existing data sources, and second, when the software saves synthesized or simulated data to the hard drive and then reads them from the hard drive again (data are saved and re-read between processes so that identical populations can be used for different analyses and experiments; see Section 4.2.4 for more details). Most trip survey data, including the data to be used in this study, come in the format of plain text, Microsoft Excel or DBF database format, none of which allow efficient access and search. The solution is to convert the data source to Microsoft Access database and then access the data with JDBC/ODBC (Java Database Connectivity/Open Database Connectivity). Combined with the use of HashMap and the more efficient Iterator method in Java programming, the data importing time was reduced to less than 1/10 of the original time needed. The data read/write efficiency was improved by the use of Java serialization¹. Initially, the data files were saved and read in XML (eXtensible Markup Language) file format, because the code library for geographical locations in Repast does not support standard Java serialization, while some Java to XML serialization packages such as XStream (XStream Comitters, 2008) and JSX (JSX Enterprises, 2008) support serialization of nearly any Java objects. However, to save Java objects (for example, agents) in XML format requires extensive formatting of the XML file, and the file size is often huge. The result was slow data reading and writing. It was later discovered that it is

¹ In Java and other programming languages, serialization is the process of converting a data structure or object into a sequence of bits so that it can be stored in a file.

faster to re-create the geographical location objects from scratch than to save them to a file and read it again. So instead of saving the location objects to the hard drive, only the indices of these location objects need to be saved. The location objects are then re-created every time the software runs, and references are then made between the objects and their indices. With the use of fixed random number generators, exact same location patterns can be replicated. This allows the use of the standard Java serialization method which is less flexible but more efficient. For the data from a test area, the I/O time is improved from nearly two minutes to around three seconds. Other than geographical locations, other objects in the software, such as agents, roads, nodes and edges in the network can also be saved by reference to their indices. The result is much improved iteration speed (the time needed to shuffle through all the agents for route and utility calculations, and movements).

Other performance tunings include the use of fast latitude/longitude retrieval, the use of an efficient random number generator, and a customized array cloning method. It was discovered that the location objects from Repast do not store decimal latitude and longitude values, but instead calculate them from radian values every time a request is received, which requires extensive computing time. Since the values are frequently used throughout the model, a simple solution is to store the decimal values to the objects when they are created. Random number generators are used throughout the model as well. For example, during the calculation of shortest path, to simulate the nature of agents' (especially pedestrian agents') incomplete and imperfect knowledge of the environment, the distance of each street is randomized every time it is used in the shortest route

algorithm, which means millions of randomization calculation each time the model shuffles through all the agents. For example, 5,000 agents, 100 streets and three different modes lead to 1.5 million calculations in each iteration. Java's internal randomization method is not efficient enough for this use. Several random number generators were reviewed and XORShiftRNG (Dyer, 2009) was selected. It is more than 40 times faster than the Java built-in random generators, with a simple test showing that the new method required only 0.368 seconds while the old method used up to 16 seconds for the same randomization task. A customized array cloning method was also created for this model, with an execution time only 2% of that of the array clone method that comes with Java.

In Java, it is known that the "clone()" method for objects does not generate a true copy of the original object. The result is only a reference copy of the object with no real content of itself other than primitive properties (properties that are expressed in numbers). So if certain non-primitive properties of the original object change, the changes influence the new object as well. For use in this study (mainly for the generation of the synthetic population), a real clone method, commonly known as deep copy, was programmed. The real clone is done by serializing the object as a string and then de-serializing it for a 100% copy of the original object. Two different serialization methods (XStream and JSX) were used for performance comparison. For a smaller data set of 300 households, JSX is about four times faster in serialization (4.6 seconds vs. 16.4 seconds) and 30% faster in de-serialization (1 second vs. 1.4 seconds). While for a large data set of 5,100 households, XStream was proven to be faster, with a serialization time of 42 seconds vs. 78 seconds for JSX. The reason may be that XStream does not create a new serialization "machine"

every time it is called, while JSX does, and the creation of these serialization machines consumes considerable computing time. Note that the native Java serialization method is not used here, because for this specific use, JSX and XStream are faster and easier to use.

4.1.5 COMPATIBILITY AND EXPANDABILITY

The modelling software was built with consideration given to data compatibility. The use of OpenMap ensures that all commonly used map types including ESRI Shapefiles and MapInfo map files are supported. As for population data, trip survey data normally come in the format of Pure Text (.txt), Microsoft Excel (.xls), DBF (.dbf), SPSS (.sav), SAS (.sas) and Microsoft Access (.mdb) format. All of the above files can be easily imported into Microsoft Access database which is used in the modelling software.

The model is developed using Java, one of the most commonly used programming language for agent-based models. The model can be expanded to incorporate more functions using external Java packages which are widely available.

4.2 SOFTWARE INTRODUCTION

MIND is composed of five Java classes representing five processes (MindReader, MindSynthesizer, MindInit, MindSpinUp and MindDaily), 12 Java classes representing 12 types of objects in the model (MindHousehold, MindAgent, MindRoundTrip,

MindTrip, MindDestination, MindRoad, MindRoadSegment, MindNode, MindEdge, MindGeo, MindText and MindMarker) and eight Java classes representing settings and other computing jobs in the model (MindSettings, MindTools, MindRouting, MindGlobal, MindGravity, MindData, MindCalibration and MindExperiment). The following sections describe the basics of the software and how the software works.

4.2.1 THE GIS MAP

The GIS map represents the structure of the road network and the locations of households and facilities. Agents move on the map based on their own route and schedule. Figure 4.4 shows a corner of a GIS map in the software. Lines (MindRoad as in the software) represent roads (black lines represent normal roads, while green lines represent pedestrian-only routes). Green colour squares (MindHousehold) on the roads represent households in the simulation. The red square (at the upper-left corner of the map, end of the street) represents one of the exits of the neighbourhood where traffic enters and exits the neighbourhood, while the blue square (at the opposite end of the same street) represents one of the locations of local facilities (including work places, schools, shopping/service facilities and transit facilities). The geographical locations of houses, facilities and exits are represented by MindGeo in the software. MindRoadSegment represents a straight line section of a MindRoad (In other words, each MindRoad contains several MindRoadSegments). The time display ("03:30:00AM") at the upper-left corner of the map is controlled by the MindText class.

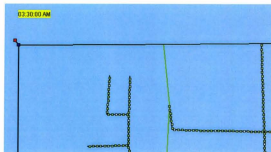


Figure 4.4: Example of the GIS map display

MindRoad

The *MindRoad* class represents the roads in the base map, and contains information on road properties. Each road is composed of a list of points (*MindGeo*) and a list of straight lines (*MindRoadSegment*) between each pair of neighbouring points. Road properties include road length, density of households on road, the nodes (*MindNode*) at each end of the road, if the road has a sidewalk on each side, if the road is pedestrian-only and if the road is an exit road (connection road to the area outside the neighbourhood). Each road is identified by a unique ID which is used in shortest route calculations.

MindRoadSegment

MindRoadSegment represents each straight line section of a road. Each segment has a unique ID, which is used to identify the location of agents during shortest route calculation and during agent movement.

MindGeo

MindGeo represents a location on the map. The location could be either the fixed location of a household or facility, or the real-time location of an agent when the agent moves on the road network. Each household and facility location is identified by a unique ID. And all locations are associated with the road they are on (onRoadID), the side of the road they are on (onEdgeID) and the straight segment they are on (onSegmentID). Each location has its latitude and longitude value stored as decimal degrees for fast retrieval.

MindText

MindText is used to display current time on the GIS map. It is simply a wrap up of the OMText class from OpenMap with an implementation of OpenMapAgent. All classes need to implement the OpenMapAgent interface for it to be displayed in the GIS map.

MindMarker

MindMarker is used to mark locations on the GIS map. It is used to mark the locations of pedestrian encounters and illustrate the spatial pattern of automobile

emissions. See Chapter 7 for the pedestrian encounter and automobile emission maps generated during the experiments.

4.2.2 THE NETWORK MAP

The network map is a network representation of the road network. Figure 4.5 shows an example of the network map in the software. In the network map, blue squares represent nodes (MindNode as represented in the software) in the network, and correspond to intersections in the GIS map. Purple lines represent edges (MindEdge) which connect nodes, and correspond to roads in the GIS map. The smaller red squares (two on each line) represent the directions of the edges. Each road corresponds to two edges with opposite directions. As mentioned in Section 3.3, edges are also used to represent sides of roads.

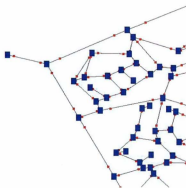


Figure 4.5: Example of a network map

MindNode

MindNode represents nodes in the network. Each node has a location which is represented by MindGeo. Each node has a unique node ID. Normally there are two opposite edges between each neighbouring node pair, but sometimes more than two exist, especially in the cases of looping streets. A "getShortestEdge()" function is written for MindNode which returns the shortest edge between any neighbouring node pairs.

MindEdge

MindEdge represents edges in the network. Each edge is identified by a unique edge ID, and contains information on whether the edge (the side of the road) has a sidewalk, and whether the edge is pedestrian-only. If a road is pedestrian-only, both edges correspond to the road are assigned pedestrian-only status. In MindSpinUp (see Section 4.2.4), traffic counts from different time periods are stored with each edge. In MindDaily (see Section 4.2.4), each edge records in real time the IDs of agents on the roads, separated by automobile and pedestrian mode. Each edge also "knows" the number of road crossings needed for a pedestrian to get from the edge to other connected edges. This crossing information is calculated during the initialization of the GIS map, and is used in shortest route calculations.

The most important function of MindEdge is to return a strength value, which could be the physical distance of the corresponding road, or the road distance weighted by road traffic, road conditions and individual perceptions. As traffic values are collected based on edges (*i.e.* the volume of traffic on each side of the road), a switch in the

software enables it to return the distance weighted by either the traffic volume on the same side as the agent is on, or on both sides of the road. The model as presented in Chapters 5 and 6 only uses the latter option (*i.e.* traffic on both sides of the road are considered).

4.2.3 AGENTS

Agents and their trips are grouped in a hierarchical structure in the model as shown in Figure 4.6. For each neighbourhood, a given number of households (*MindHousehold* in the software) are synthesized based on a real world population or study requirement. Each household may have several members (*MindAgent*), and each member may have several round trips (*MindRoundTrip*) in a day. A round trip is defined as a series of trips (*MindTrip*) that both start and end at home. Each single trip is assigned a destination (*MindDestination*). The *MindDestination* class is used to alter the location of destinations during experiments.

MindHousehold

MindHousehold represents households in the model. Each *MindHousehold* object contains household level information, as well as references to the members of the household.

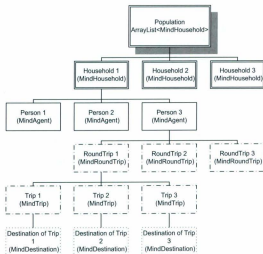


Figure 4.6: Data structure for households and trips

A special function of the MindHousehold class is to store and decide car use schedules. One of the constraints on car use is the availability of a car during a given time period. Since a household often shares the use of cars within the household, a car use list is created for each household (Figure 4.7). Each line in the list describes the schedule for one car. In each line, every four numbers form a group describing the starting time, ending time, unique ID of the person (in the household) and unique ID of the round trip (for the person). Each time a family member needs access to a car, an inquiry is sent to the car use list to find the first available car for the specified time period.

```
[201, 747, 2, 0, 861, 923, 2, 1]
[230, 584, 0, 0, 668, 819, 3, 2, 891, 980, 3, 3]
[703, 727, 0, 1, 336, 444, 3, 1, 257, 288, 3, 0, 786, 895, 0, 2]
```

Figure 4.7: An example of the car use list

MindAgent

MindAgent represents agents in the model. Each MindAgent object contains person level information, as well as references to the round trips and individual trips that the agent makes. Each agent has a set of preference values against time, cost and safety which represents taste variation. When moving on the map, agents also carry additional information including current location, trip mode, if the agent is a local resident or a visitor, and the number of pedestrian encounters and automobile traffic encounters. The GIS map in the software displays the agents in different colour according to their trip mode.

MindRoundTrip

MindRoundTrip contains round trip level information. This class is basically a wrap up of the `ArrayList<MindTrip>` class. This class facilitates round trip related calculations such as the sorting of round trips according to their disutility values.

MindTrip

MindTrip contains trip level information. The mode, route and disutility of each trip in each mode are also stored with the MindTrip object. The most important function

of the MindTrip class is to move agents on the GIS map depending on the timing of their trips.

MindDestination

MindDestination contains information on the destination of each trip, including the type of the destination (work place, school, shopping and service facilities, and social activity destinations), the location of the destination, whether the destination is outside the neighbourhood and if outside, the additional distance outside the neighbourhood.

4.2.4 DATA FLOW

The main processes in the software and the data flows between them are shown in Figure 4.8. The population data are saved after each process so that repeatable experiments can be done with the identical population.

MindReader

In this process, the model reads the population and trip data from an Access database and converts them to the data format needed in the following processes. The Access database contains real world trip survey data which are, as is common practice in trip surveys, organized into three tables:

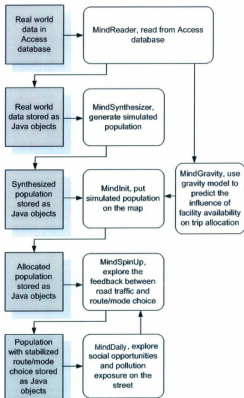


Figure 4.8: Data flow map

Household table: the household table contains household level data such as household size, number of vehicles, house type (single houses, attached/row houses, apartments), *etc.* Each household is identified by a unique household ID.

Person table: the person table contains individual level data such as sex, age, occupation, *etc.* Each person is identified by a unique person ID, as well as the corresponding household ID.

Trip table: the trip table contains trip level data such as time, origin, destination, purpose and mode of the trip. Each trip is identified by a unique trip ID, and the corresponding household ID and person ID.

MindReader reads the tables from the database using JDBC/ODBC methods, which enables Java to read from and write to compatible database formats, and groups the data into the hierarchical structure shown in Figure 4.6. The grouping is done by matching the unique IDs across the tables.

The result of MindReader is a list of households (in Java, an ArrayList of MindHousehold), which is then saved to disk using Java serialization.

MindSynthesizer

MindSynthesizer takes the result of MindReader and generates the size of population needed for use in the model. The synthesis method is explained in Section 3.2.2.

The synthesizer module groups the mode and purpose of trips into categories as required. Trip surveys usually record trip mode and purpose in detailed categories. For example, the Ottawa O-D Survey, which is used in this study, records trip purpose in 16 categories (1=Work (usual place), 2=Work related, 3=Work on the road, 4=School, 5=Shopping, 7=Recreation, 8=Restaurant (takeout), 9=Restaurant (eat in), 10=Visit friends/family, 11=Medical/Dental visit, 12=Drive someone somewhere, 13=Pick someone up, 14=Return home, 15=Other, 16=Declined/don't know), while the proposed model groups trip purposes into only five categories (work, school, shopping and services, social and return home) for a simplified structure of the model.

Another job of the synthesizer is to generate a realistic starting time for each trip. Starting times reported in trip surveys are normally rounded to the nearest tens or quarters, but in a simulation this will cause a problem as the influx of agents to the streets at the exact same time produces an unrealistically high traffic volume (and low traffic volume for other times). The generation of starting time will be discussed in Section 5.2.2.

MindInit

MindInit takes the synthesized population, and puts it on the map.

The software reads the neighbourhood map using OpenMap. Households are allocated to the streets marked with "residential street" status, with the number of households on each street determined by the density information from the map. Households are evenly distributed on each street, with half of the households on each side

of the street (the "side" information is internally recorded, but not displayed on the GIS display of the software).

Each map has an associated parameter file which identifies the number of households in the neighbourhood, the location and distribution of local facilities, and the distribution of outgoing trips among the exits. Local facilities, including work/school spaces, shopping/service facilities and transit facilities, are located at these pre-determined locations. A topological network is generated from the base map with intersections being nodes and roads being edges. This network is displayed in the network display of the model, and is used in shortest route calculation.

The allocation process works as follows. Each household is assigned a house location, and it is possible to allocate certain types of households (for example, apartments) in certain areas of the neighbourhood with specified density. For each trip, the origin is either home or the destination of the preceding trip, and the destination is assigned according to trip characteristics: For trips ending inside the neighbourhood, work/school/shopping trips are assigned to local work/school/shopping sites, while social trips are assigned to a random local household; For trips ending outside the neighbourhood, the destination is assigned to one of the exits based on the direction of the remote destination and the road network characteristics outside the neighbourhood. As the software is designed for neighbourhood level simulation, for trips that both start and end outside the neighbourhood, the corresponding agents' locations are set to be fixed at the exits where they leave the neighbourhood during the simulation.

After the allocation process, an initial route is calculated and assigned to each trip. The initial routes reflect the shortest physical distance, with no consideration of road traffic conditions.

In this study, the maps and corresponding experiments are arranged in such a way that all facilities are located close to the exits of the neighbourhood, and there is no pass-through traffic inside the neighbourhood, except on the surrounding arterials. This is to facilitate the comparison of different neighbourhood designs. For modelling efficiency, pass-through traffic on the arterials is simulated by adding a number to the traffic volume count, with no agents created to represent these trips. Social trips are considered reciprocal, so a number of agents are created to carry out incoming social trips, and the number of incoming social trips is set to be equal to the number of outgoing social trips.

The result of MindInit is again saved to disk so that the same population can be used in the next steps.

MindSpinUp

In this step, a "spin-up" process is used to explore the relationship and feedback between automobile traffic, pedestrian traffic and mode/route choice behaviour. The software first reads the base map and creates the road network, then reads the allocated households from the file saved in the initialization step (MindInit). If taste variation is considered, each agent is assigned a preference value for the corresponding factors like time and cost. These preference values can be tailored for different population groups. For example, a certain population group can be assigned lower preference values for

certain factors. Round trips are created by grouping a series of single trips with the first trip starting at home and the last trip ending at home.

The spin-up process works as follows.

Step 1: Initial traffic values on the streets are calculated from route information stored with each trip. To speed up computing and simplify the model, traffic volume numbers are counted by three time periods instead of every hour or every minute of the day. This method has been frequently used in other traffic models (for example, see Lawson, 2006; Lee *et al.* 2009). The three periods are morning peak hours, afternoon peak hours and all other times. The exact timing of these periods can be adjusted for different datasets. For the Ottawa datasets, the timings are defined as: Morning (7AM to 9AM), Afternoon (3PM to 7PM) and all off-peak times. These time periods are designed

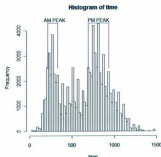


Figure 4.9: Distribution of trip starting time

(Time shown as the number of minutes since 3:30AM which is the time a simulation day begins)

by examining the trip occurrence graph (Figure 4.9) and by consulting local transportation officers.

Step 2: Agents select new modes and new routes based on utility calculations which take into account the automobile and pedestrian traffic conditions on the roads which they learnt from the previous step. The software allows three different methods of mode choice. Method 1 calculates the disutility value for each single trip and agents select their trip mode for each individual trip. Method 2 calculates the disutility of every round trip and agents choose trip mode for each round trip instead of every single trip. Method 3 adds car ownership and driver's license into consideration, so that the whole household plans car use in advance, and it is assumed that inelastic trips (round trips that involve work and school trips) get the priority on car use. For all other round trips, the priority is decided by the calculated probability of choosing the driving mode using the utility and probability functions shown in Section 3.2.1, and the round trip that has the highest probability of choosing the driving mode gets to use the car first. For each round trip that uses a car, the software will find the first car that is available for the time period in the household, and if all the cars in the household are utilized for the time period, only walking or transit modes can be selected. The schedule fitting can also have some flexibility. For example, the starting and ending time of elastic trips can be rescheduled to a certain extent (for example, ± 10 minutes) so that the round trip can fit into available time slots.

Based on the disutility calculation, a new mode and route are selected for each trip. If the utility functions uses the number of pedestrian and automobile encounters (see

Section 6.3), an extra step is taken here where the MindDaily module (see next page) is used to calculate these numbers, and the results are fed back to the spin-up process.

Step 3: The new route information is then assigned to each trip, and the software jumps back to Step 1 for a new iteration of calculations.

The “spin-up” process can be interpreted as agents learning more about road traffic conditions each day, then adjusting their mode and route choice accordingly. Or in other words, agents adapt to their environment, while the environment is in fact a consequence of agents’ actions.

It is expected that after a few iterations of spin-up, the model will reach a relatively stable state. This is determined by modal split and road traffic conditions. For each iteration of the spin-up, modal split data and road traffic characteristics are recorded and compared to the data collected in the previous iteration. If the changes in modal split and road traffic conditions are below preset levels for a certain number of iterations, the stabilized route and mode choices are then saved for use in the next step.

MindDaily

MindDaily is designed to run a full day simulation by minutes (or any other intervals as required) for all the agents. This module simulates the spatial pattern of pedestrian encounter as well as vehicular traffic emissions on the roads.

Trip survey data often record trip schedules for a whole day. In the Ottawa datasets, a survey day starts at 4:00 AM and ends at 4:00 AM the next day. Because of the

randomization of trip starting time (see the MindSynthesizer part in Section 4.2.4, also see Section 5.2.2), some trips may begin slightly earlier than 4:00 AM and end slightly later than 4:00 AM the next day. In the Ottawa model, the simulation runs from 3:30 AM to 4:30 AM of the next day.

During the full day simulation, the software records the location of each agent at each tick (which is a predetermined time interval, for example one minute or ten seconds). At each tick, the model moves agents that are already on the roads, starts trips that should begin at the tick and ends trips that have arrived at their destinations. For each agent in the pedestrian mode, the software calculates how many other pedestrians are within a predetermined distance. This proximity is used in the model as a surrogate for pedestrian encounters and potential social interaction opportunities. For convenience, the number is called “the number of pedestrian encounters” in this study. The software also determines the type of the encounter (for example, encounter with a person from inside or outside the neighbourhood, or repeated encounters). It is possible to choose neighbouring agents based on whether they are on the same side of the road, if they are on the same road, or if they are on nearby roads but still within the predetermined distance. For each street, the software calculates the traffic volume on the street, and displays different line widths to represent the traffic volume on the street. The spatial pattern and intensity of pedestrian encounters and automobile emissions can also be presented on the map (see Chapter 7 for examples of such thematic maps).

MindGravity

MindGravity is a supporting module for analyzing the relationship between trip purpose and trip distance using the gravity model. It is used to simulate the changes in trip destinations when the amount of local facilities changes. The predictions from the MindGravity module can be fed into the MindInit module. See Section 6.5 for detailed discussion on the setup and calibration of the gravity model.

4.2.5 SUPPORTING MODULES

See Appendix 1 for a description of all supporting modules

4.3 OUTPUT

The software can be customized to output various kinds of results. A few examples are provided below:

Health and environment measures: Health effects can be reflected in two measures: Pedestrian distance traveled inside the neighbourhood, and pedestrian distance traveled weighted by the amount of automobile traffic on the streets (which reflects the exposure level to automobile emissions). Environment measures include: total number of automobile trips, number of short distance automobile trips, number of possible stops for

automobiles, and vehicle distance traveled inside the neighbourhood. Based on existing studies of emission patterns (Frank *et al.* 2000; Frey *et al.* 2000; Brundell-Freij and Ericsson, 2005), it is also possible to calculate total emissions by automobile traffic inside the neighbourhood.

Modal split: Modal split and modal split by population groups can be collected from the output of the software.

Social interaction opportunities: number of pedestrians encountered and possibility of repeated encounter with the same person.

Street safety measures: For pedestrians, the number of crossings, the length of route with or without sidewalks, the length and percentage of route that are pedestrian-only routes, and the traffic volume on the pedestrian's route.

Traffic level on the roads: Traffic volume for both automobile and pedestrian traffic during different time periods of the day, as well as the whole day pattern can be observed. In this study, due to the low density of the study areas, traffic volume inside the neighbourhoods is likely to be low. But depending on the internal configuration, high traffic volume on certain streets (and the chance of congestion) is also possible.

Trip characteristics: Trips characteristics such as trip distance, distance travelled inside the neighbourhood and other characteristics can be collected, and experiments with different neighbourhoods and population data can reveal how neighbourhood forms and population characteristics influence these trip characteristics.

CHAPTER 5: STUDY AREA AND MODEL SETUP

The software platform described in Chapter 4 provides a basis for modelling neighbourhood level trip and movement patterns using trip survey data and corresponding GIS maps. Given appropriate data and maps, a neighbourhood level model can be built and calibrated, and then be used to provide predictions for specified scenarios.

In this study, a model is created based on the maps and survey data from the city of Ottawa. This chapter describes the characteristics of the study area, as well as the basic assumptions of the model.

5.1 THE STUDY AREA

Population and trip survey data from Ottawa are used in this study. Ottawa is the capital of Canada. Data from the 2001 Census show that for commuter trips, among Canada's six major urban centres (Vancouver, Calgary, Edmonton, Toronto, Ottawa and Montreal), Ottawa has the highest percentage of walking population, third highest percentage of population that utilize public transit and the highest percentage among the urban centres without a subway system, and the least percentage of population that drive to work (The City of Ottawa website). These trip characteristics make Ottawa an ideal city for studying how neighbourhood designs influence trip and traffic patterns, especially

how neighbourhood designs contribute to the greener transport modes such as walking and public transit.

5.1.1 MAPS

For the model, detailed trip survey data from seven TAZs in the city of Ottawa are used. These seven TAZs belong to three different areas of Ottawa: Barrhaven, Bridlewood and Westboro. Individual TAZ maps are created based on the GeoBase National Road Network map (GeoBase, 2005). The original map does not have road characteristics like sidewalk availability. Pedestrian-only routes are also not included in the original map. In addition, the model requires the locations of local facilities such as schools, shopping areas and work places, which are also not available in the original map. These additional features are manually added based on manual interpretation of Google Earth and Google Maps satellite imagery and Microsoft Bing Maps aerial ("bird's eye") imagery.

Figure 5.1 provides an overview of the location of these seven TAZs within the city of Ottawa. The yellow area in the upper right side of the map refers to the six TAZs which form downtown Ottawa. Westboro lies five kilometers southwest of the city center (TAZs 242 and 243), while Barrhaven (TAZs 433, 434 and 435) and Bridlewood (TAZs 500 and 501) are both suburban areas, with a distance of 17 and 20 kilometers from the downtown area respectively.

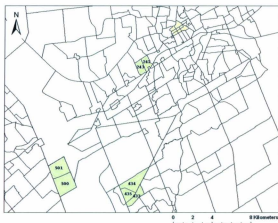


Figure 5.1: Locations of the seven TAZs within the City of Ottawa
(Downtown Ottawa shown in yellow. SOURCE: the city of Ottawa)

TAZs 242 and 243 (Figure 5.2) form the Westboro area, with 242 on the east side and thus slightly closer to the downtown area. Both the north and south side of Westboro are commercial areas and office spaces, with apartment buildings also concentrated in the south end of the area. TAZ 242 contains a large park to the east and a pedestrian-only link on the southwest side. TAZ 243, on the contrary, contains much less green space. Both TAZs have very similar household densities (number of households per square kilometer). Between these two TAZs, TAZ 242 has slightly lower density, higher percentage of single houses, higher number of vehicles per household and higher

percentage of driver's license holders. Household size is much smaller in TAZ 242 (2.043 vs. 2.661 in TAZ 243).

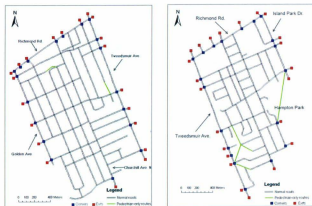


Figure 5.2: TAZ 242 (right) and 243 (left)

Note that in Figure 5.2 (and subsequent maps in this thesis), “corners” (blue squares on the map) refer to possible facility locations, and “exits” (red squares on the map) refer to the locations where traffic leaves or enters the neighbourhood. The word “corner” is used in this thesis for convenience. Such locations are not necessarily in a corner of the neighbourhood. Pedestrian-only routes are highlighted in green colour in the maps.

TAZs 433, 434 and 435 (Figure 5.3, Figure 5.4 and Figure 5.5) form the Barrhaven area, with 433 on the south side, 434 on the northeast side and 435 on the west

side. These three TAZs are quite different in size and shape from each other. TAZ 433 is separated from the other two by a railroad, with a major shopping area to the southeast side. TAZ 434 covers the majority area of Barrhaven, with several parks, a secondary school and a strip mall inside the area. To the northeast end of the area is a major transit centre with a major bus station and a rail station. TAZ 435 also contains a park in the middle and several strip malls alongside its borders. Of the three TAZs, TAZ 433 has the highest household density, but lowest household size. In general, these three TAZs share very close household and population characteristics.

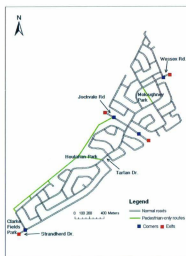


Figure 5.3: TAZ 433



Figure 5.4: TAZ 434



Figure 5.5: TAZ 435

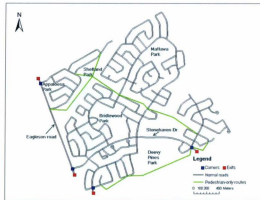


Figure 5.7: TAZ 501

5.1.2 DATA

Data corresponding to the seven TAZs are provided by the city of Ottawa. These data are from the 2005 National Capital Region (NCR) Origin-Destination Travel Survey. The survey covered more than 25,000 randomly selected households (around 5% of the total population) in the NCR region. The data provide detailed information on the sample households, including household size, house type, and number of vehicles in each household. Additionally, the data contain personal level information such as sex, age and occupation. For each individual surveyed, the data record the trip schedule on a specified date, including trip starting and ending time, trip purpose, trip mode and the origin and

destination TAZ of each individual trip. No personal identifiable information is included. The data also provide "expansion factors", which describes the statistical difference between the sample households and all the local residents. These are used in population synthesis as described in Section 3.2.2.

Additionally, for the purpose of statistical analysis to find relevant factors that influence mode and route choice behaviour, additional data covering 40 Ottawa TAZs are used. These data cover the same household, personal and trip level information as the individual level data, but are aggregated by TAZs. For the purpose of estimating traffic flows between the TAZs, aggregated employment data by economic sectors (such as education, health care, private office, *etc.*) for every TAZ in Ottawa are also used.

For comparative purposes, Nationwide Personal Transportation Survey (NPTS) data for 1990 and 1995, and National Household Travel Survey (NHTS) data for 2001 for the United States (from <http://npts.ornl.gov>), and metropolitan level trip survey data covering many US cities (from <http://www.surveyarchive.org>) are used.

5.1.3 NEIGHBOURHOOD CHARACTERISTICS

As mentioned in Section 5.1.1, the seven TAZs and three areas used in this study have distinctive characteristics. Table 5.1 provides an overview of these three areas.

Table 5.1: General description of the study area

(Source: Wikipedia.org)

<i>Region</i>	<i>TAZs</i>	<i>General description</i>
Westboro	242, 243	<p>Westboro is a thriving and trendy community close to downtown Ottawa with a lively street scene including lots of boutiques, restaurants, coffee shops, outdoors and sports stores, and an annual Westfest music festival. The neighbourhood is experiencing densification.</p> <p>The area features local churches, schools, recreation centres, two rapid-bus stations and two OC Transpo routes.</p>
Barrhaven	433, 434, 435	<p>Barrhaven is a rapidly growing suburban area located in the southwest of the urban area of the city of Ottawa.</p> <p>The region contains several schools, numerous parks and playgrounds, and a local library. A cinema and a power centre featuring Wal-Mart, Staples, Winners, Sport Chek and Loblaws are located to the south-east of the region. The region is served by five local bus routes, five express bus routes and two OC Transpo stations.</p>
Bridlewood	500, 501	<p>Bridlewood is a region in the west end of Ottawa, previously part of the City of Kanata until 2001. Both Barrhaven and Bridlewood began to develop as residential areas in the 1960s.</p> <p>The area features six elementary schools and is served by three strip malls.</p>

Table 5.2 provides a list of physical characteristics for the seven TAZs. The table shows that, while both Barrhaven and Bridlewood are post-war suburban style neighbourhoods, the household density (number of households per square kilometer) in the Barrhaven area is much higher than that of the Bridlewood area, and the density in

Barrhaven is comparable to (and in the case of TAZ 433, higher than) that of Westboro, an old and traditional grid style neighbourhood (Table 5.2). Part of the reason is that the Bridlewood area is still under active development, and thus not all the land lots are developed and used yet. The area of local green space and non-residential land uses also play an important role.

Table 5.2: Physical characteristics of the TAZs

<i>Region</i>	<i>TAZ</i>	<i>Area(square km)</i>	<i>Density (households per square km)</i>	<i>Road length (km) per square km</i>	<i>Number of intersections per square km</i>
Westboro	242	0.82	1618	16.5	88
	243	1.08	1705	16.8	76
Barrhaven	433	1.08	2259	13.3	57
	434	2.78	1378	13.8	54
	435	1.22	1701	16.1	63
Bridlewood	500	2.50	1144	10.2	35
	501	2.61	1313	11.2	39

For the TAZs, the length of roads and number of intersections (per square kilometer) are measured and compared in this study. It is intuitively plausible that with more roads (thus longer road length per square kilometer), the traffic volume distributed to each individual road would be lower, which in turn would lead to a higher safety level for pedestrians and a lower potential for congestion for automobiles. But on the other hand, depending on the design, more roads often means more intersections, which limits

automobile traffic by frequent stops and acceleration (which in turn causes higher pollution and higher chances of congestion), and more roads also means that pedestrians have to walk through more intersections. More roads may also be a challenge for maintenance tasks such as road surface maintenance and snow clearing. As evident in the data above, Westboro, with the traditional grid layout, has the highest road density (road length per square kilometer), and also the highest intersection density (number of intersections per square kilometer). Bridlewood, on the other hand, has the lowest road density and also the lowest intersection density. Note that pedestrian-only routes and intersections with pedestrian-only routes are not counted in the table.

Other than the physical differences, the three regions also have quite different population characteristics (Table 5.3). Westboro, as a “trendy” region, has smaller households, a much higher percentage of apartment dwellers and a lower percentage of single-family houses. It also has the lowest number of vehicles per household. Barrhaven has the highest number of vehicles per household and highest percentage of driver’s license holders, but this region also has a considerable number of transit pass holders, with the percentage comparable to that of Westboro. Bridlewood has the largest household size (which normally means more mature family households with parents, children, and grandparents), and the lowest percentage of apartment dwellers. It also has the lowest percentage of transit pass holders.

Table 5.3: Household and personal characteristics

<i>Region</i>	<i>TAZ</i>	<i>Household size</i>	<i>Number of vehicles per household</i>	<i>Percentage of households in detached houses</i>	<i>Percentage of households in apartments</i>	<i>Percentage of driver's license holders</i>	<i>Percentage of transit pass holders</i>
Westboro	242	2.043	1.406	55.5	24.0	68.9	16.2
	243	2.661	1.259	51.6	22.6	61.5	14.1
Barrhaven	433	2.692	1.806	62.2	2.2	72.9	15.2
	434	2.801	1.741	67.2	4.8	72.2	15.3
	435	3.201	1.859	72.4	0.9	69.3	12.0
Bridlewood	500	3.096	1.715	63.1	0	63.2	8.4
	501	2.740	1.739	73.2	3	65	10.6

Table 5.4: Percentage of trips in each mode

<i>Region</i>	<i>TAZ</i>	<i>Automobile trips</i>	<i>Transit trips</i>	<i>Walking trips</i>
Westboro	242	65.0%	14.3%	20.7%
	243	60.4%	13.8%	25.8%
Barrhaven	433	82.7%	10.5%	6.8%
	434	78.5%	12.5%	8.9%
	435	80.4%	9.4%	10.2%
Bridlewood	500	86.6%	8.7%	4.7%
	501	81.9%	6.9%	11.2%

On the trip characteristics side (Table 5.4), Bridlewood has the highest percentage of automobile trips, lowest percentage of transit trips, and lowest percentage of walking

trips. Barrhaven has slightly lower percentage of automobile trips and slightly higher percentage of transit trips. Westboro has the highest percentage of walking trips and transit trips, and the lowest percentage of automobile trips.

5.2 ASSUMPTIONS AND SIMPLIFICATIONS

Due to data availability, programming complexity and modelling feasibility, a few assumptions and simplifications were made. The following sections describe the assumptions and simplifications made and the reason for these assumptions and simplifications.

5.2.1 EXCLUSION OF CAR PASSENGER MODE

The Ottawa model does not include the mode of car passenger. The main considerations are difficulties in modelling and programming. The model focuses on neighbourhood level dynamics, and does not contain the road map and facility locations for the regions outside the neighbourhood. Thus the model would not know which trip destination is on the way to or close to another destination, which is likely to generate a shared automobile trip. Even if the model does know, inclusion of car passenger mode will also make route calculation very complex, since for each agent, the model has to go through all the potential car passengers' trip schedules to see which trips are likely to be

shared based on starting time, possible route and (dis)utility for each of these sharing possibilities.

For the seven TAZs, car passenger trips account for 13.7% of all the trips. The current solution is to remove all the car passenger trips from raw data, so that the likely demand for shared trips is eliminated.

5.2.2 TRIP STARTING TIME AND INTERVAL

During the population synthesis process, a starting time needs to be set for each trip. As discussed in Section 4.2.4, a realistic starting time has to be generated by using randomization. The software supports two methods of randomization. The simple method is to add or subtract a random number of minutes between 0 and (for example) 5 minutes to the time recorded in trip surveys, which normally record time to the nearest 10s or quarters. The other method uses a diffusion-like mechanism. For example, the diffusion method counts the number of trips in any 30-minute frame (6:00 to 6:30, 6:01 to 6:31, *etc.*), then distributes all trips evenly in the time period (for example, two trips every minute). Due to the overlapping of these 30-minute frames, a smoother starting time series will be obtained. This process can be repeated a few times for a realistic result. Figure 5.8 shows the result of the diffusion method.

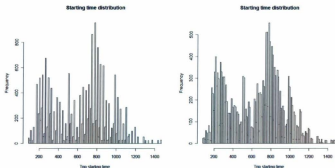


Figure 5.8: Generating starting time for trips

(Left: histogram of the raw starting times as in the survey data; right: histogram of the generated starting times. x axis refers to trip starting time - the number of minutes since 3:30AM, and y axis refers to the number of trips)

Currently the simple method of randomization is used, because the diffusion method is found to shift the starting times towards the afternoon peak time. For either method to work, for any two consecutive trips, the model needs to make sure that the randomization process would not change the sequence of the trips. The raw trip survey data show that within all the recorded trip intervals (the intervals between the starting times of any two consecutive trips), only 47 out of 7161 records are less than 15 minutes. Thus, the model is set to separate any two consecutive trips by at least 15 minutes and then do a randomization of ± 5 minutes to the starting time.

With both methods, the peak trip starting rates (the number of trips starting during a given time period) are close to each other. For example, for TAZ501, both methods

generate peak trip starting rates of around 400 for any 15-minute frame and around 100 for any 3-minute frame.

5.2.3 RANDOM ALLOCATION OF HOUSEHOLDS AND FACILITIES

Due to privacy concerns, household locations are normally not available in travel survey data. In the model, a random allocation process is used to put the synthesized households on the map. As previously mentioned, in the Ottawa model, inside trips are set to end at one of the facility locations or houses in the neighbourhood, while outgoing trips are set to end at one of the exits of the neighbourhood. The selection of a specific facility location or exit is a probability based random choice, with the probability of using each facility location determined by the amount of facilities available at the location, while the probability of using each exit determined by studying trip flows between all TAZs in Ottawa as well as the characteristics of the road networks in Ottawa.

Figure 5.9 shows an example of the trip flow map generated by the MindGlobal module (see Appendix 1). The map is generated based on the survey data. Since trip flows between some TAZ pairs can be very low, regions instead of TAZs are used (except for the region where the study TAZ is in, detailed TAZ to TAZ traffic flow is identified). The regions are generated based on the Cycling District Map provided by the city of Ottawa which divides the metropolitan area into 11 regions. The probability of using each exit is estimated based on the trip flow map and the road map of Ottawa.

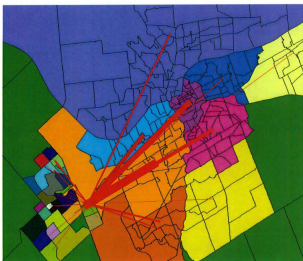


Figure 5.9: A map of work trip flows between regions in Ottawa
(The amount of trip flow is represented by line width)

Table 5.5 shows changes in selected trip and traffic characteristics with different random allocation simulation runs for TAZ 501. While trip characteristics for a specified individual in the region would change with different random allocation, the regional average, as well as average values among the same trip purpose group or trip mode group, remains stable. Experiments carried out later also prove that the change of random number generators (which means the generation of different sets of random locations) has little influence on modal split predictions.

Table 5.5: Influences of the random allocation process

<i>Measures</i>	<i>Run 1</i>	<i>Run 2</i>	<i>Run 3</i>	<i>Run 4</i>	<i>Run 5</i>
Total pedestrian encounters	37925	39056	37511	39906	38107
Average trip length inside (work trips) (metre)	1723.81	1715.42	1717.23	1723.66	1701.36
Average trip length inside (driving mode) (metre)	1792.97	1782.09	1783.53	1799.14	1784.88
Crossings for pedestrians, mean	6.72	6.72	6.87	6.58	6.95
Crossings for pedestrians, standard deviation	4.23	4.28	4.4	4.24	4.38

5.2.4 TRIP DISTANCE ESTIMATION

The trip survey data used in this study do not contain trip length. For each trip, only the origin TAZ and the destination TAZ are recorded. In the model, the length of each trip is estimated by the distance between the TAZs. These distance measures were provided by the city of Ottawa, representing road distances between geographical centers of the TAZs.

The distance or length for each outgoing trip is estimated as:

$$D_{trip} = D_{raw} - L_{origin} \pm rL_{destination} + D_{inside}$$

In the equation, D_{raw} refers to the raw distance between the centers of the TAZs as provided by the city of Ottawa, L_{origin} and $L_{destination}$ refer to the distance from the geographical center of the origin or destination TAZ to the exit point of the TAZ, and

D_{inside} refers to the distance travelled inside the origin TAZ. r is a random number between 0 and 1, which reflects the fact that the actual distance travelled inside the destination TAZ is not known to the model. The length of each incoming trip is estimated in a similar manner. For the TAZs in the outskirts of the city, the distance numbers between the TAZs as well as between these TAZs and inner area TAZs are not available, as these outskirts TAZs each occupy a large area, and the geographical centers are often not a good representation of the population center or the activity locations. For these peripheral TAZs, the distance between them and the inside TAZs are estimated to be a random number between 25 and 75 kilometres based on map characteristics of the region.

The graphs in Figure 5.10 refer to the distance distribution of all trips, work trips, school trips, social trips and returning-home trips respectively. For all graphs except the graph for work trips, the curve fitted on the graph represents a gamma distribution. This conforms to the findings of Zhang and Mohammadian (2008). In the case of work trip distances, normal distribution fits better than gamma distribution. The fitting of gamma distribution for school trip distances is not very satisfactory. The exceptions with work and school trips may be due to the inelastic nature of such trips, as the destinations of such trips are often fixed. Compared to other types of destinations, most work trip destinations (*i.e.* work places) tend to be further away from home and the distance numbers concentrate between 10 and 30 kilometers, while for most other type of trips the distance numbers concentrate between 0 and 10 kilometers. Note that while this study does not make direct use of the distribution pattern, it shows an approach to generate synthetic trip distances, or to verify the trip distances generated by other methods.

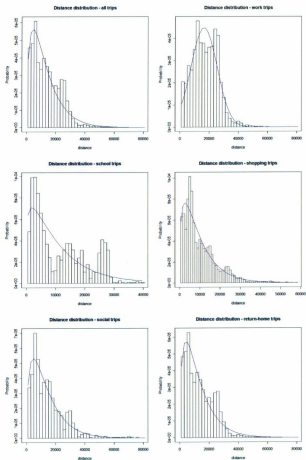


Figure 5.10: Distribution of trip distances measured in metres

5.2.5 PEDESTRIAN ENCOUNTER

It is suggested that the chance of social interaction is positively related to the number of pedestrian encounters (see Section 2.2). As mentioned in Section 4.2.4, in the model, pedestrian encounters are interpreted as the proximity between two pedestrian agents, and the number of pedestrian encounters is calculated by counting the number of pedestrians who pass within a given distance of the pedestrian in question during a trip. The distance can be set to an arbitrary number. In this study, it is set to be 25 metres. Experiments show that the number of calculated pedestrian encounters increases linearly with the distance settings (Figure 5.11). As the software module that counts pedestrian encounter runs at 20-second intervals, and a pedestrian walks 24 metres in 20 seconds, the 25 metres setting would capture all the agents within a 20-second walking distance.

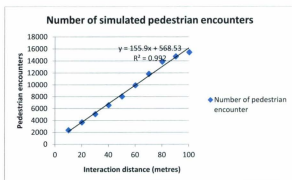


Figure 5.11: Relationship between pedestrian encounter numbers and the distance setting

Different time intervals together with corresponding distance settings will change the calculated encounter count for an individual region. But experiments show that the number of encounters remains roughly linear with the distance setting, and for two regions, the results remain comparable with each other (Table 5.6).

Table 5.6: Time interval, distance setting and pedestrian encounter numbers

<i>Time interval setting</i>	<i>Interaction distance</i>	<i>Calculated encounters for region A</i>	<i>Calculated encounters for region B</i>	<i>Count of region A as percentage of region B</i>
60s	75m	7412	5143	144%
50s	62.5m	6967	5028	139%
40s	50m	6251	4548	137%
30s	37.5m	5299	3861	137%
20s	25m	4644	3248	143%

The results show that, used in a linear utility equation, the distance and time interval settings would have only slight influence on the output of the model. This is also confirmed by experiments. Note that the number of automobiles encountered during a trip is calculated using the same method and the results follow the same roughly-linear pattern.

CHAPTER 6: MODEL FORMULATION AND CALIBRATION

Based on the software platform discussed in Chapter 4, and the assumptions and simplifications discussed in Chapter 5, a model can be established to simulate the influence of neighbourhood design on daily trip pattern in urban neighbourhoods.

As discussed in Section 3.2.1, utility (or disutility) is used in this study to calculate mode choice. There is no universal agreement on how utility should be defined and calculated. Depending on data availability and simulation requirements, different utility functions have been utilized in different studies in the past. In this study, two different utility function formulations will be explored. Model 1.0 (Section 6.1) uses a simple version of the utility function, with utility given as a function of time, cost, safety and individual preferences, with the variation in preferences represented by a normal distribution. The safety factor is represented by the use of "perceived distance", which takes into account pedestrians' perception of road characteristics (such as availability of sidewalks and pedestrian-only routes) and traffic conditions (such as the volume of automobile traffic and pedestrian flow). The advantages and problems associated with this formulation are discussed in Section 6.2. To address the problems faced by model 1.0, model 2.0 (Section 6.3) explores the use of socio-economic characteristics of households and individual residents to represent differences in individual perceptions and preferences in the calculation of utility values. Section 6.4 discusses the calibration of model 2.0, and the advantages and problems associated with it. A further variation of the model formulation, with socio-economic characteristics directly representing preference

variations, is explored (model 2.1, see Section 6.3). The gravity sub-model and its calibration are discussed in Section 6.5. A sensitivity analysis of model 2.0 is provided in Section 6.6.

A model is built to simulate a real-world process or phenomenon. The validity of a software model can be examined using two criteria: First, the model should correctly implement the intended algorithm, and there should be no error related to the software code and structure. This is often called the "internal verification" of a model, and in this study, it is done by repetitive testing of individual software code blocks, modules and the whole software package. Second, the output of the model should be a reasonable representation of the real-world process or phenomenon being modelled, and the parameters of the model should be optimized so that the model output closely fits the corresponding real-world data. This is called the "calibration" of the model. It should be noted that "verification", "validation" and "calibration" of a model are closely related. The validity of a model can only be tested with a correctly calibrated version of the model, and the calibration process should also assist in the verification of the model by discovering design and programming errors.

A complex system model is dynamic and stochastic in nature. For example, in this study, travel behaviour of an individual in the neighbourhood is complex. The choices in a trip including time, purpose, mode and route are influenced by a number of internal and external factors. Some of these factors may have fixed values, such as the number of cars in the family, or the availability of pedestrian-only routes in the neighbourhood; but some factors are dynamic in nature, such as traffic conditions on the roads and the chance of

pedestrian encounters. Even if all the external conditions are the same, human decisions are still dynamic and stochastic in nature, partly due to imperfect knowledge of the whole system and also because of the uncertainty nature of human decisions.

Compared to traditional models, agent-based models can better represent system dynamics as collective outcomes of individual decisions and interactions. However, these models still partly rely on mathematical relationships to include or exclude factors that the modeller finds important or related. It is not possible to include all the factors that might be related to choice behaviour, and the model is only expected to explain a portion of the real world trip-making characteristics (Mierzejewski and Jackson, 1992).

Thus, the output of a complex system model is not to be expected to conform exactly to the real world data. Instead, the calibration and validation of such systems are often done "by applying it in as many situations as possible" (Engelen and White, 2007), and the pattern of the results (rather than the details of the results) is often used in comparison to real-world data. For example, in land use change studies, results of CA or ABM models are often examined in terms of measures like fractal dimensions (Andersson *et al.* 2002) or techniques such as fuzzy comparison which compares the patterns of the maps instead of the characteristics of each individual land lot (Power *et al.* 2001; Hagen, 2003).

It was proposed that the model could be validated by testing it with multiple neighbourhoods in multiple metropolitan areas with available data, and the pattern of the results compared to that from real world data. However, as travel behaviour is heavily

influenced by the socio-economic environment including social traditions and economic conditions, data from different cities face comparability problems. Thus, the model to be presented only uses data from TAZs inside the city of Ottawa for calibration. However, extensive tests and experiments are still carried out to examine the dynamics and uncertainties of the model and to ensure that the model produces realistic and reasonable results. Trip survey data from the 2005 National Capital Region (NCR) Travel Survey for the city of Ottawa are used in the calibration of the model.

6.1 MODEL 1.0

Model 1.0 presents a simple version of the utility function formulation. As discussed in Section 3.2.1, agents decide their mode and route choice based on (dis-)utility. Assuming that agents' taste variation values are normally distributed, the taste variation value of an individual agent can be presented as:

$$\chi = N(\mu, \sigma^2)$$

where χ refers to a normally distributed variable, and μ and σ refer to the mean and standard deviation of the corresponding normal distribution. While it is assumed that the values that represent the preferences or tastes of individuals form a normal distribution, there is no agreement on the characteristics of the distribution. Experiments in this study found that a distribution with a mean value of 1 and a standard deviation of 0.05 to 0.06 generates good results.

Considering taste variation, the utility function can be written as:

$$U = \alpha\chi_t T + \beta\chi_c C + \gamma\chi_s S$$

where, T , C and S refer to the time, cost and safety values that are associated with the trip. α , β and γ are coefficients which effectively decide the weight of time, cost and safety factors in the calculation of the utility value U . χ_t , χ_c and χ_s represent perturbations to the coefficients due to variations in perceptions or tastes among individuals.

Pedestrian safety is often regarded as one of the most important factors that influence pedestrian mode and route choices (see Section 2.2), and one of the objectives of the model is to find out how neighbourhood designs influence pedestrian safety. For pedestrians, the risk of a vehicle-pedestrian collision exists when they walk along the road and when they cross the street. Sidewalks and pedestrian-only routes would likely decrease the risk, while increased road traffic would likely increase the risk. In the model, the availability of sidewalks and pedestrian-only routes, the number of road crossings and the traffic level on the roads are used to calculate the safety measures for pedestrians. These factors not only influence pedestrian safety and thus mode choice, they also directly influence route choice. To include the factors directly in shortest route calculations and create a dynamic routing mechanism in the model, the safety measure is presented in the form of "perceived distance", so that if the safety level of a street/street section is higher, the perceived length of the street would be lower, and pedestrians are more likely to use the street. The safety measures for driving and transit are assumed to be fixed values as the study concentrates on the safety of pedestrians.

The calculation of the pedestrian safety measure is in three steps:

Step 1: To take road traffic into consideration, it is suggested that pedestrians try to avoid streets with a high volume of automobile traffic, while they are attracted to streets with more pedestrians. Taste variation may also exist so that some pedestrians are more sensitive to road traffic volume while others are less sensitive. Thus, the influence of automobile traffic and pedestrian traffic can be calculated as:

$$p_j = \chi_j (N_j + 1)^{-\alpha_j}$$

Where p_j refers to the influence of traffic in mode j on pedestrians, with j being either automobile mode or pedestrian mode. N refers to the hourly traffic volume on a street during the time period (morning peak, afternoon peak or off-peak period) when the trip occurs. The number is increased by one so that when the traffic volume is 0, the influence value is 1. χ_j refers to the normally distributed perturbation applied to traffic volume in mode j that represents the effect of difference among individuals. It is assumed that traffic volume increase is more perceivable by pedestrians when the value is small and less perceivable when the traffic volume is already high. Figure 6.1 shows the influence curve for automobile traffic when $\alpha = 0.05$. Experiments showed that such formulation produces stable and realistic traffic patterns.

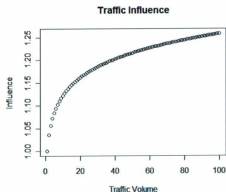


Figure 6.1: Influence of traffic volume

Step 2: As automobile traffic decreases the desirability of a street, while pedestrian traffic increases its desirability, the combined influence is calculated as:

$$L_i = (1 \pm R) \frac{P_{car}}{P_{ped}} D_i$$

where D represents the physical length of a street, and p refers to the influence of automobile or pedestrian traffic as calculated in Step 1. To account for the stochastic nature of human decisions, and agents' imperfect knowledge of the neighbourhood (including road characteristics and traffic conditions), the perceived distance is randomized, and R represents the extent of randomization. The randomization is needed

for the model to produce a realistic traffic pattern, see Section 6.6 for more details. The result (L) is the perceived length for the street considering the influences of traffic volume.

Step 3: Road conditions further influence this perceived length. Available sidewalks would make streets seem less risky, and pedestrian-only routes mean even lower risk levels. On the other hand, more road crossings increase the risk level of the trip. For each trip, the route is formed by a number of streets together with a number of crossings. The “combined perceived distance” is calculated as the sum of the perceived length of all streets plus the length of all crossings (*i.e.* the distance to walk through an intersection). If taste variation is considered for the valuation of sidewalks, pedestrian-only routes and crossings as well, the equation can be written as:

$$S_{walking} = \sum_{i=1}^n p_{sidewalk} \chi_{sidewalk} p_{pedonly} \chi_{pedonly} L_i + p_{cross} \chi_{cross} D_{cross}$$

where p represents the influences of sidewalks, pedestrian-only routes and crossings on perceived distance. L is the value calculated in Step 2 which represents the traffic-weighted length, and D represents the crossing length. χ refers to the normally distributed variation in the influence of sidewalks, pedestrian only routes and crossings respectively that represent individual differences in knowledge, preferences and tastes. The calculated S value is then used in the utility equation as presented at the beginning of this section.

Finally, the probability of choosing one of the transport mode is decided based on a random choice function:

$$P_{\text{MODE1}} = \frac{e^{rU_{\text{MODE1}}}}{e^{rU_{\text{MODE1}}} + e^{rU_{\text{MODE2}}} + e^{rU_{\text{MODE3}}}}$$

where U is the utility value calculated for each mode, and r is a control parameter that influences the probability of choosing the mode with the highest utility value (see Section 3.2.1 for detailed discussion).

6.2 CALIBRATION AND ANALYSIS OF MODEL 1.0

As described in Section 4.2.4, it is expected that with appropriate parameters, the spin-up process will produce modal split values which stabilize after a few iterations. The calibration is done by manually changing the model parameters and observing whether the modal split stabilizes, and whether the stabilized values approximate the actual values as closely as possible.

Table 6.1 shows the simulated modal split values generated by the calibrated model versus the actual values. The results show that the model can generate a modal split that closely follows actual patterns. Simulation results for transit trips tend to be less accurate, probably due to the fact that transit routes and schedules are not considered in the model.

Table 6.1: Observed and predicted modal split

Region	TAZ	Actual observations (percentage)			Simulation results (percentage)		
		Driving	Transit	Walking	Driving	Transit	Walking
Westboro	242	65.0	14.3	20.7	72.2	9.5	18.3
	243	60.4	13.8	25.8	65.6	8.5	25.9
Barrhaven	433	82.7	10.5	6.8	77.4	15.6	7.0
	434	78.5	12.5	8.9	74.3	13.4	12.3
	435	80.4	9.4	10.2	79.9	11.0	9.1
Bridlewood	500	86.6	8.7	4.7	85.6	8.7	5.8
	501	81.9	6.9	11.2	80.2	8.5	11.4

As described in Section 4.2.4, three different mode choice methods are programmed in the modelling software. In method 1, agents select trip mode for each individual trip. In both methods 2 and 3, it is assumed that agents select a single transport mode for all trips in a round trip. While it is possible that individuals may choose mixed-mode for a round trip (for example, walk to the destination and take a bus back), in reality, for the study areas, very few (less than 2%) round trips use mixed-mode, *i.e.* most round trips use a single mode for all the trips within the round trip. Calculation of mode choice based on round trips greatly improved the simulation speed, while also avoided the problem of generating unrealistic mixed-mode trips.

The difference between method 2 and method 3 is that in method 3, the availability of a driver's license and the availability of a car are taken into consideration in the mode choice process. Experiments showed that with appropriate model parameters,

both methods can generate realistic modal split values. However, further examination showed that when the mode choice results are examined by trip purposes or population groups, the result by method 3 is structurally more realistic. Table 6.2 shows an example of the modal split values generated using methods 2 and 3. Both methods generate realistic modal split patterns, with similar overall prediction error on transit and walking, and slightly higher prediction error on driving for method 2.

Table 6.2: Modal split prediction for TAZ 435 using two mode choice methods

<i>Modal split</i>	<i>Driving</i>	<i>Transit</i>	<i>Walking</i>
Actual observation	80.4	9.4	10.2
Prediction using method 2	77.7	11.1	11.1
Prediction using method 3	79.9	11.0	9.1

However, when the simulation results are examined by trip purposes (Table 6.3), it is found that method 3 generates very accurate driving trips, and the prediction errors for all three modes are significantly lower than the prediction error using method 2.

Table 6.3: Prediction error using two mode choice methods

	<i>Prediction error using method 2</i>		<i>Prediction error using method 3</i>	
	Work and school related trips	All other trips	Work and school related trips	All other trips
Driving	-15.8%	7.2%	-2.4%	1.1%
Transit	193.5%	9.8%	50.0%	15.7%
Walking	160.0%	-51.1%	18.6%	-24.1%

The result supports the assumption in method 3 that inelastic trips like work and school trips are often given priority on car use. It also shows that the model predictions can be improved by adding hierarchical mode choice algorithms and restrictions.

The model is expected to generate not only a realistic modal split, but also a realistic traffic flow pattern on the roads in the neighbourhoods. The ideal way would be to obtain traffic counts for each street or each intersection, and then compare the traffic levels generated by the model with the observed traffic levels on the streets. However, this method is not feasible as traffic counts are often only available for major intersections or major screen lines in a city, and are less likely to be available for neighbourhood streets or intersections. Also, these data are also often expensive to obtain. Furthermore, traffic counts normally only cover automobile traffic, and not pedestrian traffic which is the main focus of this study.

As discussed at the beginning of this chapter, the calibration of a complex system model can be achieved by comparing the pattern of the results rather than the detailed numbers. The pattern of pedestrian route choice has been examined in several studies. It is found that "shortest/fastest route" is the most important factor that influences pedestrians' route choice (Schlossberg *et al.* 2007), and that about 75% walking trips took the shortest path (Verlander and Heydecker, 1997). Furthermore, it is found that for walking trips to the same destination, 74% of pedestrians used a consistent route on the previous five occasions (Schlossberg *et al.* 2007). The study areas in both studies have a mixed grid and loop/curve design. Based on these patterns, the parameters that influence pedestrians' route choice can be estimated and a realistic pedestrian traffic flow pattern

can be generated. Table 6.4 shows the estimated pattern for the seven TAZs. In general, grid-based neighbourhoods see a lower percentage of trips using the shortest route, and much less consistency of route choice. This can be explained by the characteristics of the street network. In a grid-based neighbourhood, a pedestrian can often choose among many parallel streets with close route distances. Thus in such a neighbourhood, a pedestrian is less likely to choose the absolute shortest route which may be only several metres shorter than the alternative routes. But in a neighbourhood mainly containing loop roads and cul-de-sacs, a pedestrian often faces much less choice as the length of the alternative routes is often significantly longer.

Table 6.4: Predicted patterns of pedestrian route choice behaviour

TAZ	242	243	433	434	435	500	501
Percentage of trips using the shortest route	72.0	53.3	71.1	82.3	77.8	78.0	74.1
Consistency of route choice	64.9	41.4	74.0	81.6	78.8	82.2	86.0

The results show that model 1.0 is able to generate realistic modal split and traffic patterns, and the model fit can be further improved by adding hierarchical mode choice algorithms to the model. But the random taste variation values still mean that the "taste" generated by the model could be significantly different from the "true taste" of the agent. By applying a hierarchical mode choice algorithm so that different trip purposes are treated differently in the model, the model is able to generate better predictions for each individual trip purpose. It is theoretically possible to add more hierarchies to the mode choice algorithm so that certain household types, agent types or trip types are given

special treatment and that the model can generate better predictions for such household, agent or trip types. However, this will create a very complex model structure which is extremely hard to calibrate.

6.3 MODEL 2.0

As discussed above, the prediction errors for individual population groups in model 1.0 might be reduced by adding more hierarchies to the mode choice algorithm, but this will create a complex model structure. The trial-and-error calibration method used in model 1.0 is also inefficient. It not only requires extensive time and effort, but also lacks a theoretical, and especially, a mathematical, basis.

Given the problems, an alternative approach was taken. It is suggested that individual differences in terms of their perceptions and preferences towards the utility of a trip (or more specifically, towards the time, cost and safety values associated with an individual trip) can be at least partly explained by their socio-economic characteristics, and that there is a direct relationship between socio-economic characteristics and travel patterns. The raw data used in this study contain detailed information about each household and individual's socio-economic characteristics and corresponding mode of choice for each trip, along with trip characteristics including starting time, purpose and a rough distance (as determined by the distances between TAZs). By using correlation and logistic regression analysis, it is possible to discover which socio-economic or utility factors contribute to the actual mode choice. These factors can be integrated directly into

the utility equations, and the mode choices can be presented as a multinomial logit (MNL) model. The parameters of such a model can be estimated using maximum likelihood estimation (MLE).

To find out which socio-economic characteristics are most likely to influence the choice of each mode (and then only these selected characteristics need to be tested in the next steps), correlation analyses were carried out on aggregated data from 40 TAZs in Ottawa. For each TAZ, the data contain the number of households and vehicles in the TAZ, the characteristics of the households (the types of residence – single/detached houses, semi-detached houses, townhouses and apartments), total population and the characteristics of the population (including the population counts for each sex, age and employment groups, as well as the population counts for driver's license and transit pass holders). The numbers not only show the characteristics of the region, they also show the average characteristics of the households and the individuals (when the numbers are divided by household count or population count of the region). Thus, to find out how these characteristics influence at different levels, three correlation analyses were carried out respectively for the raw data, the raw data divided by the household count of each TAZ, and the raw data divided by the population count of each TAZ.

Table 6.5 shows the correlation analysis results for the average household characteristics (raw numbers divided by the total household count). Factors that are strongly and positively related to the driving mode are: number of vehicles per household, percentage of households living in single/detached houses, household size, number of individuals aged under 14 and between 35 and 49 per household, number of driver's

license holders per household, number of full-time workers, homemakers and children per household. This reveals a picture of the households where car trips are more likely to be taken: large households with more vehicles and driver's license holders in the household, living in single/detached houses, with family members including a middle-aged full-time worker, a homemaker, and children under 14. On the other hand, the factors that are negatively related to the driving mode are percentage of households in apartments, and number of individuals aged between 20 and 24 per household. These two factors are both positively related to the walking mode. This gives a picture of the households where walking trips are more likely to happen: young people between 20 and 24 living in apartment buildings. A few other factors that are positively related to the driving mode are also negatively related to the walking mode, including number of vehicles per households and number of children per households. This seems to mean that households with more vehicles and more children are more likely to choose the driving mode at the expense of the walking mode. For public transit, this correlation analysis shows that households with more individuals aged between 15 and 19 and between 50 and 54, those with a transit pass and those who are students are more likely to take public transit.

Correlation analysis for the raw data (see Table II.1 in Appendix II) shows that factors strongly related to the number of automobile trips are number of vehicles, number of households in detached houses and number of full-time workers. The number of transit pass holders is shown to be strongly related to the number of transit trips. Factors related to walking trips include number of households in apartments and number of person aged between 20 and 24.

Table 6.5: Correlation analysis of the household average characteristics

<i>Household average</i>	<i>Automobile trips</i>	<i>Transit trips</i>	<i>Walking trips</i>
Vehicles per household	.897**	-0.31055	-.673**
Percentage of households in single houses	.714**	-0.12846	-.362*
Percentage of households in semi-detached houses	-0.13793	0.082823	0.127649
Percentage of households in townhouses	-0.06515	0.104278	-0.24488
Percentage of households in apartments	-.830**	0.049637	.691**
Percentage of households in other types of residences	-.339*	-0.0502	-0.06623
Household size	.752**	0.013017	-.332*
Number of male persons per household	.680**	-0.00094	-0.24739
Number of female persons per household	.734**	0.02356	-.374*
Age 4 or under, per household	.457**	-.436**	-.391*
Age 5 to 9, per household	.577**	-.335*	-.392*
Age 10 to 14, per household	.665**	0.08533	-0.2994
Age 15 to 19, per household	.336*	.548**	-0.2216
Age 20 to 24, per household	-.554**	.376*	.688**
Age 25 to 34, per household	-0.18187	-0.1472	0.142326
Age 35 to 44, per household	.519**	-0.2226	-0.29033
Age 45 to 49, per household	.495**	0.308267	-0.20943
Age 50 to 54, per household	.325*	.477**	-0.16058
Age 55 to 64, per household	0.055606	0.311975	0.034471
Age 65 to 74, per household	0.107833	-.402*	-0.06002

Age 75 or over, per household	-0.0869	-0.30587	-0.05626
Number of driver's license holders per household	.716**	0.062208	-0.24442
Number of transit pass holders per household	-0.14471	.948**	-0.08023
Full time workers per household	.508**	0.171018	-0.25934
Part time workers per household	0.067307	.357*	-0.03257
Students per household	0.053336	.577**	0.29357
Retirees per household	0.053279	-0.24191	-0.08988
Homemakers per household	.446**	-.505**	-.379*
Persons with other job types, per household	-0.19486	-0.0746	0.303961
Children per household	.588**	-.428**	-.445**

(** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed))

Correlation analysis for the individual average data (see Table II.2 in Appendix II) shows that number of vehicles per person is positively related to driving, while negatively related to transit and walking. The percentage of population between 20 and 24, and the percentage of population who are students are each negatively related to driving, while both factors are positively related to transit and walking. Other factors shown to be negatively related to transit trips are percentage of population under 9, between 35 and 44, the percentage of population who are homemakers, and children. Other factors positively related to transit include percentage of the population aged between 15 and 19, and between 50 and 54, and percentage of the population with transit passes. For walking,

factors showing negative correlations are the percentage of population under 9 and the percentage of population who are children.

Besides the correlation analyses based on aggregated data, a logit regression analysis was also performed based on the household and individual level survey data for the seven TAZs used in this study. The analysis shows the correlation between trip modes and the factors listed in Table 6.6.

Table 6.6: Summary of the logit regression analysis result

<i>Mode</i>	<i>Factors</i>
Driving	Age, driver's license, occupation, transit pass type, trip purpose
Transit	Age, driver's license, transit pass, trip distance
Walking	Age, driver's license, occupation, telecommute, trip purpose

Combining the results from the correlation analyses and the logit regression analysis, and excluding the factors that might be correlated with each other (for example, age groups are found to be correlated with factors such as number of children in the household and whether the person is a student), the socio-economic factors considered in the final models are listed in Table 6.7:

Table 6.7: Factors considered in the final models

<i>Mode</i>	<i>Factors</i>
Driving	Number of vehicles per household, whether the person lives in an apartment
Transit	Whether the person holds a transit pass, whether the person is a student, the number of children in the household
Walking	Whether the person is a student

Note that “whether the person lives in an apartment”, “whether the person holds a transit pass” and “whether the person is a student” are dummy variables. The value of a dummy variable is one if the statement is true, and zero if the statement is false. For example, for an agent, if he/she lives in an apartment, then the dummy variable “whether the person lives in an apartment” has a value of one.

6.4 CALIBRATION OF MODEL 2.0

In model 1.0, utility is calculated as a weighted total of time, cost and safety measures. No personal characteristics are included in the utility calculation. While the equation uses a random number drawn from a normal distribution to represent taste variation, the taste variation value does not take into account an individual’s personal characteristics. Thus, while the model is usually able to generate a realistic modal split, there is often a great discrepancy between the predicted mode and the actual mode taken for individual agents and individual population groups.

Without the random taste variation values, the utility equation would become:

$$U = \alpha T + \beta C + \gamma S$$

In model 1.0, pedestrian safety is measured as the cumulative total of the “perceived length” of each street and road crossing. While this enables the model to easily simulate traffic feedbacks and dynamics, it causes a problem in calibration as the non-linear equation can only be calibrated based on trial-and-error experiments. To solve

this problem, a linear equation is proposed to include road characteristics and traffic conditions:

$$S = \sum_j \gamma_j R_j$$

where R refers to one of the j factors that represent road characteristics and traffic conditions, and γ is a parameter effectively controlling the weight on the influence of the corresponding factor. Examples of the factors are the percentage of route distance that has available sidewalk, the percentage of route distance that is pedestrian-only, the number of road crossings on route and the volume of vehicular traffic encountered.

Based on the discussions in the preceding section, certain socio-economic characteristics of agents can also be directly added to the equation:

$$U = \alpha T + \beta C + \sum_i \delta_i E_i + \sum_j \gamma_j R_j$$

where E refers to one of the i socio-economic characteristics that are considered in the equation, and δ is the weighting parameter. Note that the utility function for different modes may have different sets of socio-economic variables.

Selection of variables (including socio-economic variables, and variables that represent road characteristics and traffic conditions) and estimation of the equation parameters is done using Biogeme (Bierlaire, 2003), a freeware package designed for the development of research in the context of discrete choice models. Biogeme, short for Bierlaire Optimization toolbox for GEv Model Estimation, has been used in many

transportation and neighbourhood studies in recent years (Vrtic *et al.* 2005; Dugundji, 2008; Takama and Preston, 2008; Potoglou, 2008; Vega and Reynold-Feighan, 2009). Biogeme uses a maximum likelihood estimation (MLE) method to estimate parameters of multinomial logit (MNL) models.

The selection of variables follows the following criteria:

1. Variables strongly correlated to the choice of specific mode;
2. Minimum correlation between selected variables;
3. Passes *t*-test as shown in Biogeme;
4. The estimated variable parameter has a correct sign - *i.e.* it reflects the influence of the corresponding variable in a correct direction.

Based on extensive experiments with different variables in the equations, the final utility equations used in this study are:

$$\begin{aligned}
 U_{car} &= \alpha T_{car} + \beta C_{car} + \delta_{vehp} Vehp + \delta_{apar} Apar + \gamma_{csto} Csto + \gamma_{cind} Cind + \phi_{nexp} Timpr, \\
 U_{pass} &= \alpha T_{pass} + \beta C_{pass} + \delta_{pass} Pass + \delta_{stud} Stud + \delta_{kids} Kids + \phi_{purp} Purp + C_{trans}, \\
 U_{walk} &= \alpha T_{walk} + \beta C_{walk} + \delta_{stud2} Stud + \gamma_{pedo} Pedo + \gamma_{pind} Pind + \gamma_{cenc} Cenc + \gamma_{penc} Penc + C_{walk}
 \end{aligned}$$

Table 6.8 explains the variables used in the utility equations

Table 6.8: List of variables in the utility equations

<i>Type</i>	<i>Name</i>	<i>Explanation</i>
Trip-specific variables	<i>T</i>	Time needed for the trip
	<i>C</i>	Monetary cost for the trip
	<i>Timp</i>	Whether the trip occurs in the morning peak period
	<i>Purp</i>	Whether the trip is inelastic (<i>i.e.</i> a work or school trip)
Socio-economic variables	<i>Vehp</i>	The number of vehicles per person in the household
	<i>Apar</i>	Whether the person lives in an apartment
	<i>Pass</i>	Whether the person holds a transit pass
	<i>Stud</i>	Whether the person is a student
	<i>Kids</i>	The number of children in the household
Route characteristics for driving	<i>Csto</i>	The number of potential stops inside the neighbourhood
	<i>Cind</i>	The driving distance inside the neighbourhood
	<i>Pedo</i>	The percentage of route distance that is pedestrian-only
	<i>Pind</i>	The walking distance inside the neighbourhood
Route characteristics for walking	<i>Cenc</i>	The volume of automobile traffic encountered
	<i>Penc</i>	The volume of pedestrian traffic encountered
Constants	<i>C_{tran}</i>	Constants that represent effects not explained by the factors included in the equations
	<i>C_{walk}</i>	

While there are three equations for calculating three utility values, only two constants are used: C_{tran} and C_{walk} . The reason is that in a MNL model, if each utility

function has a constant representing factors not explained by the other variables in the equation:

$$\begin{aligned}U_1 &= \alpha T_1 + \beta C_1 + \theta_1 \\U_2 &= \alpha T_2 + \beta C_2 + \theta_2 \\U_3 &= \alpha T_3 + \beta C_3 + \theta_3\end{aligned}$$

Then

$$\begin{aligned}U_2 - U_1 &= \alpha(T_2 - T_1) + \beta(C_2 - C_1) + (\theta_2 - \theta_1) \\U_3 - U_1 &= \alpha(T_3 - T_1) + \beta(C_3 - C_1) + (\theta_3 - \theta_1)\end{aligned}$$

As the probability of choosing a certain mode out of three modes is

$$P_1 = \frac{e^{\alpha T_1}}{e^{\alpha T_1} + e^{\alpha T_2} + e^{\alpha T_3}} = \frac{1}{1 + e^{\alpha(T_2 - T_1)} + e^{\alpha(T_3 - T_1)}}$$

It is clear that only the difference between the constants matters when calculating mode choice probabilities. Thus, there is no need (and in fact it is not possible) to estimate three constants for a discrete choice model with three alternatives (Ortuzar and Willumsen, 2001).

An important note here is that the estimation of equation parameters through Biogeme is done by using a maximum likelihood approach, so that the estimated model parameters will maximise the probability of the model to reproduce the observed data set. The problem is that the simulation in this study is done by randomly allocating synthesized household units in the neighbourhood, as the actual locations of the households are not known (the addresses were not recorded in the trip survey due to

privacy concerns). Thus, for an individual agent in the model, the percentage of route length that is pedestrian-only, the volume of automobile and pedestrian traffic encountered, and the distance travelled inside the neighbourhood may be totally different from the situation encountered by the corresponding real-world resident (as in the survey data). Thus, the mode prediction based on these data from the model is likely to be totally different from the actual mode taken. The parameters estimated using such data are also likely to be insignificant or incorrect. The current solution is to use neighbourhood average values. So in the equations, *Csto*, *Cind*, *Pedo*, *Pind*, *Cenc* and *Penc* refer to the average number of car stops inside the neighbourhood, the average travelling distance by car inside the neighbourhood, the average percentage of route length with pedestrian-only status, the average travelling distance for pedestrian trips inside the neighbourhood, the average volume of automobile traffic encountered by all pedestrians, and the average volume of pedestrian traffic encountered by all pedestrians. The reasoning here is that agents choose their trip mode based on their perception of the road and traffic conditions and social environment of the whole neighbourhood and that mode choice behaviour is influenced by prior experience in the neighbourhood and perception of the neighbourhood, and not solely decided by the conditions to be expected for a single trip (for example, see Lund, 2002; Ewing *et al.*, 2004; Humpel *et al.* 2004).

Table 6.9 lists the parameter values for the calibrated model. In the table, the sign of the value for each parameter means the direction of influence of the corresponding variable on the utility measure. For example, for the driving mode, more vehicles in the household and longer average driving distance inside the neighbourhood increase the

Table 6.9: Calibration result of model 2.0

<i>Name</i>	<i>Value</i>	<i>Std err</i>	<i>t-test</i>	<i>p-value</i>	<i>Robust Std err</i>	<i>Robust t-test</i>	<i>p-value</i>
α	-0.00021	4.14E-06	-50.61	0	6.81E-06	-30.77	0
β	-0.000182	1.40E-05	-13.04	0	1.44E-05	-12.66	0
δ_{vehp}	0.719	0.051	14.1	0	0.116	6.17	0
δ_{apar}	-1.32	0.0659	-19.95	0	0.057	-23.1	0
γ_{csto}	-0.079	0.0208	-3.8	0	0.0186	-4.25	0
γ_{cind}	0.000268	7.54E-05	3.56	0	7.17E-05	3.74	0
φ_{timp}	-0.629	0.0383	-16.4	0	0.0369	-17.04	0
δ_{pass}	2.76	0.096	28.71	0	0.102	27.06	0
δ_{su2}	1.12	0.0583	19.19	0	0.06	18.67	0
δ_{kids}	-2.15	0.17	-12.64	0	0.171	-12.56	0
φ_{purp}	1.33	0.0619	21.5	0	0.0643	20.72	0
C_{gas}	-3.76	0.192	-19.58	0	0.194	-19.36	0
δ_{su3}	2.23	0.0476	46.82	0	0.0436	51.11	0
γ_{podo}	7.15	1.34	5.33	0	1.32	5.4	0
γ_{prnd}	-0.000428	9.53E-05	-4.49	0	9.81E-05	-4.36	0
γ_{ccnc}	-0.0394	0.00553	-7.14	0	0.00488	-8.08	0
γ_{penc}	0.0325	0.00694	4.69	0	0.00632	5.15	0
C_{walk}	-0.4	0.17	-2.35	0.02	0.167	-2.4	0.02

utility value (and in turn increase the likelihood of choosing driving mode), while more potential stops inside the neighbourhood, if the agent lives in an apartment and if the trip happens in the morning peak time decrease the utility value (and thus decrease the

likelihood of choosing driving mode). For public transit, if the person holds a transit pass, if the person is a student, and if the trip is an in-elastic trip like work and school trip, the likelihood of choosing public transit is greater, while more children in the household decreases the likelihood of choosing public transit. For the pedestrian mode, if the person is a student, the higher the average percentage of pedestrian-only paths on the trip route, and the higher the average volume of pedestrian traffic encountered, the greater the likelihood of choosing the pedestrian mode; while higher average walking distance inside the neighbourhood and higher average volume of automobile traffic encountered decrease the likelihood of choosing pedestrian mode.

With socio-economic factors in the utility equations, the model is found to generate good modal split results. Table 6.10 shows predicted modal split values.

Table 6.10: Modal split predictions based on model 2.0

<i>Region</i>	<i>TAZ</i>	<i>Observations (percentage)</i>			<i>Predictions (percentage)</i>		
		Driving	Transit	Walking	Driving	Transit	Walking
Westboro	242	65.0	14.3	20.7	66.9	11.3	21.8
	243	60.4	13.8	25.8	67.5	9.0	23.4
Barrhaven	433	82.7	10.5	6.8	77.8	14.1	8.0
	434	78.5	12.5	8.9	78.1	12.8	9.1
	435	80.4	9.4	10.2	79.2	9.6	11.1
Bridlewood	500	86.6	8.7	4.7	84.9	8.5	6.6
	501	81.9	6.9	11.2	83.3	7.4	9.3

Compared to the predictions of model 1.0 using random taste variation values (see Section 6.2), the new predictions are generally closer to actual observations. As the utility equations include five household and population characteristics (*Vehp*, *Apar*, *Pass*, *Stud* and *Kids*) and two trip level characteristics (*Timp* and *Purp*), the model is able to generate more accurate predictions for population and trip groups based on these criteria. Furthermore, because of the cross-reference between all these factors, the prediction accuracy for population groups based on other criteria may also be improved. Table 6.11 shows that for agents with transit passes, model 2.0 provides much better modal split predictions.

Table 6.11: Comparing mode predictions for agents with transit passes

<i>Scenarios</i>	<i>Driving</i>	<i>Transit</i>	<i>Walking</i>
Actual observation	276	434	0
Prediction with model 1.0	152	548	10
Prediction with model 2.0	281	400	29

While model 2.0 generates good results, taste variation is not directly presented in the model. It is suggested that instead of using random taste variation values, it is possible to use a set of socio-economic characteristics to represent agents' taste variation (Fowkes and Wardman, 1988). This leads to the formulation of model 2.1.

For pedestrians, the neighbourhood and traffic conditions considered in the equation could be extracted into a new variable, which denotes safety- and social-related factors for pedestrians:

$$S_{walking} = \gamma_{pede} P_{edo} + \gamma_{pind} P_{ind} + \gamma_{cenc} C_{enc} + \gamma_{penc} P_{enc}$$

A similar variable can also be created for driving trips:

$$S_{driving} = \gamma_{cdo} C_{do} + \gamma_{cind} C_{ind}$$

Using P to denote the two trip characteristics $Timp$ and $Purp$, the utility equations can be rewritten as:

$$U = \alpha T + \beta C + \gamma S + \varphi P + \sum_i \delta_i E_i$$

where E_i refers to the set of socio-economic factors included in each equation for the corresponding mode.

Traditionally, taste variation is simulated by including a random variation in the coefficients $\alpha, \beta, \gamma, \dots$ to reflect different people's different perception or evaluation of each factor. Assuming that χ is a normally distributed random variable:

$$\chi = N(\mu, \sigma^2)$$

Then with taste variation and socio-economic characteristics in consideration, the utility equation can be written as:

$$U = \alpha\chi T + \beta\chi C + \gamma\chi S + \dots + \sum_i E_i$$

As Fowkes and Wardman (1988) suggested, the socio-economic variables can be added directly into the coefficients, thus transforming the equation to:

$$U = (\alpha_0 + \sum_i \alpha_i E_i)T + (\beta_0 + \sum_i \beta_i E_i)C + (\gamma_0 + \sum_i \gamma_i E_i)S + \dots$$

Each socio-economic variable can be entered into one or more coefficients (Rizzi and Ortuzar, 2003), depending on the nature of the problem and the prior knowledge of the modeller. The advantage of this transformation is that taste variation is directly represented by socio-economic variables in a deterministic manner. Comparing to the random taste variation values, the calculated "taste" using socio-economic variables is more likely to represent the real "taste" of the agents. This method has been used in several other studies (for example, see Rizzi and Ortuzar, 2003).

Based on experiments using different socio-economic variables in different coefficients in the equation, the final optimized equations for model 2.1 are:

$$\begin{aligned} U_{car} &= (\alpha + \alpha_{11}Vehp + \alpha_{12}Apar)T_{car} + \beta C_{car} + \gamma S_{car} + \varphi_{time}Timp \\ U_{transit} &= \alpha T_{transit} + (\beta + \beta_{11}Stud + \beta_{12}Kids)C_{transit} + \varphi_{time}Pwtp + C_{transit} \\ U_{walk} &= (\alpha + \alpha_{31}Stud)T_{walk} + \beta C_{walk} + \gamma S_{walk} + C_{walk} \end{aligned}$$

The estimated parameter values are shown in Table 6.12. As shown in the table, for the driving mode, more vehicles in the household increases the likelihood of choosing the driving mode, while the likelihood is lower if the agent lives in an apartment. For public transit, if the person is a student, the likelihood of choosing public transit is increased, while more vehicles in the household decreases the likelihood. For the pedestrian mode, if the person is a student, the likelihood of choosing the pedestrian mode is increased. Comparing the coefficients for the three transport modes, it appears that people who choose to drive tend to value time more than people who choose to take

public transit or walk, and for those who choose driving, people who live in households with more vehicles per person tend to value time more than people who live in apartments. Of course, with only one or two socio-economic characteristics in each coefficient, such generalization may have neglected other important factors. For example, for people who choose public transit, it may be that they have transit passes or have better access to transit facilities, instead of having lower valuation for time.

Table 6.12: Calibration results for model 2.1

<i>Name</i>	<i>Value</i>	<i>Std err</i>	<i>t-test</i>	<i>p-value</i>	<i>Robust Std err</i>	<i>Robust t-test</i>	<i>p-value</i>
α	-0.000259	4.33E-06	-59.87	0	7.84E-06	-33.02	0
β	-0.000668	8.42E-06	-79.32	0	9.05E-06	-73.85	0
α_{11}	0.00156	3.98E-05	39.13	0	4.75E-05	32.79	0
α_{12}	-0.000823	6.41E-05	-12.85	0	4.99E-05	-16.49	0
γ_{car}	0.589	0.22	2.68	0.01	0.201	2.94	0
ψ_{ump}	-0.791	0.0339	-23.34	0	0.0331	-23.91	0
β_{21}	0.000142	1.60E-05	8.84	0	1.63E-05	8.71	0
β_{22}	-0.000416	4.30E-05	-9.69	0	4.44E-05	-9.37	0
ψ_{purp}	1.29	0.0594	21.67	0	0.0617	20.87	0
$C_{transit}$	-1.1	0.103	-10.66	0	0.0936	-11.77	0
α_{31}	0.000123	4.77E-06	25.85	0	6.22E-06	19.82	0
γ_{walk}	0.698	0.0716	9.74	0	0.0647	10.78	0
C_{walk}	-0.187	0.104	-1.8	0.07	0.0958	-1.95	0.05

The difference between the modal 2.0 and model 2.1 where socio-economic factors are directly used in the equation coefficients is listed in Table 6.13:

Table 6.13: Difference between model 2.0 and 2.1

<i>Model version</i>	<i>Parameters used</i>	<i>Initial log-likelihood</i>	<i>Final log-likelihood</i>
2.0	18	-48111.528	-16076.235
2.1	13	-48111.528	-16939.748

While the second approach has the advantage of being able to represent taste variations with household and personal characteristics, the final log-likelihood value in Table 6.13 shows that the prediction would be less accurate than the initial approach. Table 6.14 shows the predictions based on the model 2.1. The prediction errors tend to be slightly larger comparing to Table 6.10.

Table 6.14: Modal split predictions using model 2.1

<i>Region</i>	<i>TAZ</i>	<i>Observations (percentage)</i>			<i>Predictions (percentage)</i>		
		<i>Driving</i>	<i>Transit</i>	<i>Walking</i>	<i>Driving</i>	<i>Transit</i>	<i>Walking</i>
Westboro	242	65.0	14.3	20.7	67.4	11.5	21.2
	243	60.4	13.8	25.8	68.3	8.7	22.9
Barrhaven	433	82.7	10.5	6.8	77.9	14.0	8.1
	434	78.5	12.5	8.9	78.4	12.3	9.3
	435	80.4	9.4	10.2	79.1	10.3	10.6
Bridlewood	500	86.6	8.7	4.7	84.5	8.8	6.7
	501	81.9	6.9	11.2	83.3	7.6	9.1

It should be noted that the predictions based on model version 1.0 (where random taste variation values are used), 2.0 (where socio-economic characteristics are added to the utility equations) and 2.1 (where socio-economic characteristics are directly used in variable coefficients) share some common patterns of prediction errors. Transit trips tend to be underestimated in TAZ 242 and 243, but overestimated in TAZ 433. Predictions for the other regions appear to be much more accurate. There may be several reasons. First, as mentioned in Section 6.2, transit routes and schedules are not considered in the model. The model assumes that agents walk to transit stops and then they can take transit to any destination at any time. Second, as the MNL approaches (models 2.0 and 2.1) estimate equation parameters by maximizing the probability of generating correct mode choice predictions, regions with greater populations and trips are in effect given higher weights in the process. Thus the predictions will favour larger regions while creating higher errors for smaller regions like TAZ 242 and 243. Third, it is also likely that these prediction errors are caused in part by factors that are not included in the model. For example, model 1.0 uses only two household/agent characteristics: whether the agent has a driver's license and the number of cars in the household. Model 2.0 uses only five household/agent factors and two trip level factors. It is possible that the factors which correspond to the prediction errors are not included in the model, either because they are not available in the original data, or because they are found to be statistically insignificant during the factor-selection process. Fourth, it is also likely that the samples (which represent 5% of the whole population) are not a good representation of the local population.

It should also be noted that, in this study, any variables showing wrong signs in the Biogeme analysis are excluded. For example, it is expected that if the socio-economic variable "whether the person holds a transit pass" is used in the utility equation for the transit mode, the sign for the coefficient of this variable would be positive, *i.e.* if the person holds a transit pass, the utility value for choosing the transit mode will increase. But under certain circumstances, Biogeme may report a negative sign for the transit pass variable. A wrong sign often appears when the variable is not related and should not be included, or there exists correlation between the variable and other existing variables in the equations. While the inclusion of these wrong-sign variables may improve the overall prediction accuracy of the model (and in some cases, they do), it is theoretically less sound to include such variables. The inclusion of such wrong-sign variables may increase the fit of the model to a particular dataset, but it is likely to cause greater prediction error for other datasets.

The distribution of the taste variation values calculated based the socio-economic characteristics was examined in this study. For example, in the disutility equation for driving, the coefficient for time is represented as $\alpha + \alpha_1 Vehp + \alpha_2 Apar$. Figure 6.2 shows the distribution of the coefficient values. In Section 6.1, the random taste variation values are obtained from a normal distribution with a mean value of 1. For comparison, the distribution of the time coefficient is also transformed into a distribution with a mean value of 1. Analysis shows that the standard deviation is 0.97, and the kurtosis value is 99.95, which shows that the distribution has a much higher peak and a heavier tail than a normal distribution (the curve in the graph). Note that the factors used to represent taste

variations in this example have very limited values. Only two factors are used: the number of vehicles per person, and whether the agent lives in an apartment. For all the agents, the former factor has only ten possible values while the latter factor has only two possible values. Thus, while the results show the pattern that most people do have taste variation values close to each other, the distribution characteristics (standard deviation, kurtosis, etc) as estimated by Biogeme may not be an accurate representation of the real values.

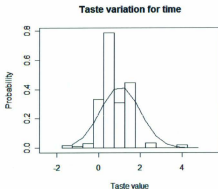


Figure 6.2: Taste variation for time for driving trips as estimated using Biogeme

6.5 A GRAVITY MODEL FOR SHOPPING AND SERVICE TRIPS

To examine the influence of the availability of local facilities, a sub-model based on the gravity equation was created. The city of Ottawa has 344 TAZs. For each TAZ, data are available for employment in each economic sector (for example, school, shopping and services). These numbers are used as representations of the activity opportunities available in each economic sector in the TAZs. However, many TAZs have few or no jobs in specific sectors as shown in the data; the available aggregated trip data also show few or no trips between many TAZs. Thus, the data from many TAZs may be found statistically insignificant if used alone.

To solve this problem, concentric distance zones instead of TAZs are used for development of the gravity model. From each TAZ, the whole city is divided into 16 distance zones (with the first zone being the TAZ itself), and the second zone less than 4 km, $3^{rd} < 8$ km, ..., < 56 km and > 56 km). Figure 6.3 shows an example of the concentric distance zones with the base TAZ being 242.

In the gravity model, the attractiveness of each distance zone is calculated as

$$A_i = E_i^{\alpha} / d_i^{\beta}$$

where A_i is the attractiveness value, E_i is the total employment in a specific economic sector in distance zone i , and d_i is the distance of the concentric zone from the base TAZ.

Then trips are assigned to each zone based on its relative attractiveness:

$$P_i = \frac{A_i}{\sum_j A_j}$$



Figure 6.3: The concentric distance zones circling TAZ 242
(Darker colour means closer distance to TAZ 242)

The results show that work and school trips do not follow the gravity model, probably due to the inelastic nature of such trips. For shopping and service trips, the estimated α and β value are 0.98 and 1.96 respectively, which is in line with other gravity model estimations for shopping trips (for example, see Hansen, 1959; Jones and

Simmons, 1990). Figure 6.4 shows the gravity model predictions for TAZ 242 and 433. While the model represents a good fit of the actual observations in general, some distance zones have larger prediction errors. There are two main reasons: First, both trip and employment data are aggregated at the TAZ level, and the TAZs in Ottawa vary

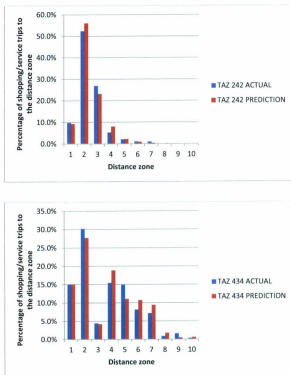


Figure 6.4: Gravity model predictions for TAZ 242 and 434

significantly in size and shape, thus the distance zones created in the gravity model are often fairly irregular (see Figure 6.3). Second, the distance used in the sub-model is the road distance between centres of the TAZs, which may differ from the actual trip distances, especially for short distance trips and trips to TAZs with large areas.

6.6 SENSITIVITY ANALYSIS

A simulation model will unavoidably have uncertainties that are intrinsic to the data and to the model itself. These include errors of measurement, absence of information and poor or partial understanding of the system. Sensitivity analysis is the process to determine the quality of the model specifications. Sensitivity analysis is used to identify the factors that contribute most to the output variability, interactions between factors and the optimal regions within the parameter space of values. The difference between sensitivity analysis and calibration is that sensitivity analysis is used to see if the model outcome will alter dramatically or unexpectedly because of changes in parameters, while calibration is used to make the model outcome conform to real world data.

For the Ottawa model, sensitivity analysis was carried out for version 2.0 of the model, since the output of this version represents the best fit to actual observations. In the sensitivity analysis, the following equation coefficients or model parameters were tested:

1. Coefficients for time, cost and safety in the disutility functions (α , β and γ);

2. Coefficients that control the influences of automobile traffic and pedestrian traffic;

3. The model parameter that controls the extent of route randomization which represents imperfect knowledge of the agents and uncertainties in choice behaviour.

Table 6.15 shows the sensitivity analysis result. The analyses are done by changing the specific parameter as listed in the table while keeping all other parameters unchanged. In the table, *D*, *I*, and *S* indicate changes in modal split numbers as the coefficients (listed in categories 1 and 2 above) change. “*D*” means “decrease”, “*S*” means “relatively stable” and “*I*” means “increase”.

The directions of change shown in the table above mostly conform to expectation. Notable results include: higher β value (which means decreasing the importance of cost, as β has a negative sign) increases transit trips, but car trips remains stable; higher γ_{cmd} and γ_{cmd} value (which means decreasing the importance of the number of potential stops for cars – as γ_{cmd} has a negative sign, and increasing the importance of the driving distance inside the neighbourhood) increases the number of car trips while decreasing both transit and walking trips. The number of transit trips remains stable in most situations.

Table 6.15: Direction of influence for the global parameters

(D: decrease, S: stable, I: increase)

Parameter	Direction of Change	Modal split		
		Driving	Transit	Walking
α	I	D	S	I
β	I	S	I	D
γ_{peds}	I	D	S	I
γ_{pind}	I	D	S	I
γ_{cenc}	I	D	S	I
γ_{penc}	I	D	S	I
γ_{cto}	I	I	D	D
γ_{cind}	I	I	D	D
$\alpha_{\text{automobile}}$	I	D	S	I
	D	S	S	S
$\alpha_{\text{pedestrian}}$	I	D	S	I
	D	S	S	S

Note that the coefficients that control the influence of automobile and pedestrian traffic ($\alpha_{\text{automobile}}$ and $\alpha_{\text{pedestrian}}$) influence both mode and route choices. A higher value of these two coefficients is likely to cause pedestrians to be highly (and unrealistically) concentrated on certain pedestrian-friendly roads, as pedestrians avoid automobile traffic, but are attracted to pedestrian-friendly streets including streets with sidewalks, pedestrian-only routes and streets with more social interaction opportunities. The

concentration of pedestrian traffic on such roads further increases the attractiveness of these roads, and the utility of choosing the pedestrian mode. This in turn creates more pedestrian traffic. Figure 6.5 shows an example of an extreme scenario where pedestrians are highly concentrated on the pedestrian-only routes in TAZ 501.

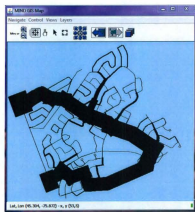


Figure 6.5: An extreme example of pedestrian traffic concentration.

This concentration effect is offset by the randomization factor in the model, which represents the fact that individual agents do not have perfect knowledge of the road and traffic conditions, as well as individual differences in taste and preference which means that they do not always choose the route with the best deterministic utility. Figure 6.6 shows the distribution of pedestrian traffic with randomization considered in the model.



Figure 6.6: Pedestrian traffic distribution with randomization considered

The change in the extent of randomization not only influences trip distribution among the streets, it also directly influences modal split. Experiments show that traffic distribution and modal split both stabilize when the extent of randomization increases from 0 to around $\pm 10\%$. Further increase of the randomization factor causes higher level of fluctuation between iterations for modal split and traffic distribution.

6.7 SUMMARY

Three different model formulations were explored in this chapter. The calibration process shows that each formulation has its own advantage and disadvantage. Model 1.0,

with its simple formulation, is able to generate realistic trip and traffic patterns. However the model suffers from tedious calibration process and relatively inaccurate predictions for individual population groups. While this can be improved by adding more constraints to the mode choice algorithm, the result of such algorithm alternation is often a very complex model structure that is difficult to calibrate and justify.

With the introduction of socio-economic characteristics directly into the utility equations, model 2.0 shows a model formulation which not only is easier to calibrate, but also produces results that better fit the observation. Furthermore, model 2.1 shows that such socio-economic characteristics can be directly integrated into the coefficients of the utility equations, thus can be interpreted as a direct representation of taste variation.

The sensitivity analysis shows that the variation of certain model parameters may lead to dramatically different output patterns, and that an appropriate randomization process which reflects the uncertainty nature of human knowledge and behaviour is useful in the model.

With the calibrated model, and the gravity sub-model as introduced in Section 6.5, different experiments will be carried out to explore how daily trip patterns are influenced by neighbourhood designs in general and by detailed design features such as availability of facilities and pedestrian-only routes.

CHAPTER 7: EXPERIMENTS

As proposed in Chapter 1 and 2, the model is designed to discover how different neighbourhood designs influence modal split, trip characteristics, traffic patterns and the related aspects of daily life including social interaction opportunities, health, pollution, pedestrian safety and congestion probabilities. Four neighbourhood designs are examined in this study. The traditional grid and post-war suburban designs are important because they are widely used throughout North America. In the recent years, the neo-traditional design has also been implemented in many neighbourhoods in the US and Canada. As discussed in Section 2.1, each of these designs has its own advantages, but also faces some criticisms. Experiments with the calibrated model are designed to discover the overall influences of these designs on trip and traffic patterns, and also the influences of some of the internal characteristics of these designs (for example, the location of facilities and the availability of pedestrian-only routes). The fused grid design, as a new approach to neighbourhood design, is also evaluated in this study.

To evaluate the influence of these designs, two sets of experiments were used. The first set of experiments uses seven hypothetical neighbourhood design maps, representing the four neighbourhood designs mentioned above, with two maps each for the traditional grid, the post-war suburban and the neo-traditional designs respectively, and one map for the fused grid design. Each map represents one or more of the most distinguishing characteristics of the corresponding neighbourhood design. The second set of experiments uses three layout maps, with the first one being the real-world map of the Barrhaven

region in Ottawa, with the other two being planning scenarios representing the neo-traditional and fused grid designs applied to Barrhaven. The calibrated model is used to find out how people react to different neighbourhood designs by choosing different transport modes and routes, and how these decisions in turn generate distinctive traffic and trip patterns.

Neighbourhood designs influence trip and traffic patterns through their internal characteristics. Thus, experiments and evaluations are carried out not only for each design in its entirety, but also for variations of some of the internal characteristics of each design, including the location and number of facilities, the availability of pedestrian-only routes, the population density and the population structure. By changing the location and number of local facilities, the availability of pedestrian only routes and the density of the neighbourhoods, experiments show how these internal characteristics of the neighbourhood designs influence modal split numbers, traffic patterns, and related aspects of daily life. Experiments are also carried out to discover how neighbourhood design affects different populations.

For each design, the influence of the design on several aspects of trip characteristics and daily lives of residents is studied. Modal split numbers represent the percentage of trips expected for each transport mode. Social interaction opportunities for pedestrians are reflected in the pedestrian encounter numbers (as discussed in Section 2.2, the number of pedestrian encounters is believed to be associated with the chance of social interaction). Total pedestrian distance and the pollution exposure index (see Section 7.1.2) represent health related effects of a neighbourhood design, while total vehicle trip

distance and the number of potential stops for cars are surrogates for the amount of pollution generated by automobile trips. Both the number of road crossings for pedestrians and the pollution exposure index reflect pedestrian safety issues associated with automobile traffic. The congestion probabilities are shown by the peak traffic volume on the streets. Furthermore, thematic maps were created to visually demonstrate the spatial pattern of pedestrian encounters, vehicle emissions and vehicular traffic flow.

The experiments were carried out by hypothetically putting the resident population in different neighbourhood designs. This allows simulation of the scenario in which a neighbourhood design is transformed into a new one, or in which certain aspects of an existing neighbourhood design change, while in both cases all residents remain living in the area. The experiments were designed to find out how traffic patterns, trip characteristics and daily lives in the neighbourhood will change under these circumstances.

The experiments were carried out under the common assumption that the trip demand of local residents is not influenced by the design changes; only the destinations, transport modes and routes will change. It has been suggested that neighbourhood design may have the effect of inducing or suppressing trip demand, especially for elastic trip types like shopping and social trips. The term "induced demand" is mostly used in the context of automobile traffic, and refers to the increase in the number or length of automobile trips with the improvement of road networks. "Suppressed demand", on the other hand, refers to the decrease in such traffic or trips when road network conditions deteriorate. The changes include both newly generated trips and existing trips made by a

different mode (*i.e.* modal shift, which is covered by this study) (Cervero and Hansen, 2002). It is commonly believed that induced demand for a certain mode is associated with improvements in road networks or facilities that are associated with the mode. For example, as mentioned above, induced automobile traffic is often associated with improvement of urban road or highway systems. Induced pedestrian traffic, on the other hand, is normally associated with improvement in pedestrian friendly routes and facilities such as sidewalks, pedestrian-only routes, traffic controls and shorter access distances to facilities. While the model in this study does not simulate the effect of induced or suppressed latent traffic (*i.e.* newly generated or cancelled trips), the results already show that the neo-traditional and fused grid designs are associated with more pedestrian traffic. Increased use of the pedestrian mode is associated with benefits such as more pedestrian-only routes, shorter walking distances to facilities, less exposure to automobile emissions, and less automobile traffic. With induced latent traffic, it is likely that the advantages of these two neighbourhood designs for pedestrians will be more evident, as the characteristics of these two designs are likely to induce pedestrian trip demand while suppressing automobile trip demand. Of course, as frequently mentioned in this study, urban neighbourhoods are complex systems, and the actual influence of introducing induced demand into the model may be more complex.

The chapter is organized into three sections. In Section 7.1, experiments are carried out using the seven hypothetical neighbourhood maps. After a general description of the design maps (Section 7.1.1), the “replacement” experiments are used to find the changes in trip characteristics, traffic patterns and encounter probabilities if one of the

Ottawa TAZs were to be transformed to each of the seven hypothetical designs in turn (Section 7.1.2). Further experiments show how the internal characteristics of these designs, including the location and number of facilities (Section 7.1.3), the availability of pedestrian-only routes (Section 7.1.4), the population density (Section 7.1.5) and the population structure (Section 7.1.6), influence modal split and trip patterns. In Section 7.2, experiments are carried out using the three design maps for the Barrhaven region. A general evaluation is given in Section 7.2.1, while the influence of pedestrian-only route availability is evaluated in Section 7.2.2. The findings from these experiments are discussed in Section 7.3.

7.1 THE HYPOTHETICAL NEIGHBOURHOODS

For the existing neighbourhood forms including traditional grid, post-war suburban and neo-traditional neighbourhoods, different variations of the designs exist in different parts of the world. The size of the blocks, the number of loops and cul-de-sacs, layout of the road networks and location of local facilities differ from one neighbourhood to another, even when they are of the same neighbourhood type. The definition of the word "neighbourhood" is also never clear. Many researchers simply use this word to represent a census tract (Galster and Booza, 2007), a naturally formed area or a historically formed area. For example, in the fused grid design, a neighbourhood is defined as one of the four blocks surrounded by the twinned arterial (CMHC, 2002). But the size of each block, which is 400×400 metres, is much smaller than a typical post-war

suburban or neo-traditional development (for example, see Stone *et al.* 1992), and is also much smaller than the size used in Transit Oriented Development (TOD), which is a 10-minute-walk radius from a transit stop (see Calthorpe (1993)), or in much other neighbourhood research, a 10-minute-walk distance from side to side (for example, see Kirtland *et al.* (2003); Addy *et al.* (2004)). The distance of a 10-minute-walk can be translated into 720 metres using the standard in the U.S. Manual on Uniform Traffic Control Devices (MUTCD) (U.S. Federal Highway Administration (FHWA), 2003).

For the purpose of this study, two maps were created for each of these three neighbourhood types, and one map as created by CMHC is used to represent the fused grid design. To make the maps comparable with each other, all the maps are constructed as 800×800 metres (approximately half a mile) in area. The area size is the recommended size for a transit-oriented neighbourhood development, and half-mile grids are also widely used in North America for different kinds of neighbourhoods. As the layout maps are created to represent the most distinctive characteristics of each neighbourhood type, they are likely to produce results that are unique to each of the designs.

Figure 7.1 and Figure 7.2 show two traditional grid designs. The only difference between the two designs (abbreviated as TG1 and TG2) is the block size. TG2 has a block size that doubles that of TG1. This is used to evaluate the influence of block size. As mentioned in Section 5.1.1, the red squares on the map refer to the exits of the neighbourhood, while the blue squares ("corners") refer to the possible location of local facilities.

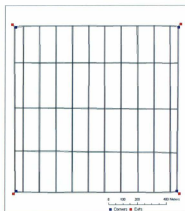


Figure 7.1: Traditional grid 1 (TG1)



Figure 7.2: Traditional grid 2 (TG2)

Figure 7.3 and Figure 7.4 (PW1 and PW2) represent two different post-war suburban neighbourhood layouts. Both maps are created based on residential neighbourhoods in Richmond, BC. Many neighbourhoods in this area have the size of around 800×800 meters (or half mile by half mile), which make it possible to use the neighbourhood maps from this area without much change. Of the two maps, PW1 uses cul-de-sacs extensively, while PW2 uses more loop roads. Both neighbourhoods are surrounded by arterial roads and both have five access roads connecting the arterial roads and the inner residential area, which makes them highly comparable to each other.

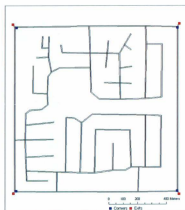


Figure 7.3: Post-war suburban 1 (PW1)

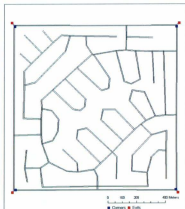


Figure 7.4: Post-war suburban 2 (PW2)

The two neo-traditional neighbourhood layouts (NU1 in Figure 7.5 and NU2 in Figure 7.6) are also constructed based on real-world neo-traditional neighbourhoods. NU1 is based on a neighbourhood in southeast Calgary, Alberta, while NU2 is based on a neighbourhood in east Denver, Colorado. Of the two maps, NU1 uses more loop roads, while NU2 shares more similarity with a traditional grid neighbourhood, except with extensive use of garage access roads (marked blue in the maps), which are also used in NU1. With the use of loop roads, NU1 also has a much larger effective block size than NU2. Note that the garage access roads (in blue colour) are built to connect the garages at the back of the houses to the main roads. These roads are often elevated and have no through traffic, thus have very little traffic volume throughout the day. The green coloured lines represent pedestrian-only routes.

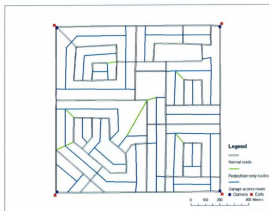


Figure 7.5: Neo-traditional neighbourhood 1 (NU1)

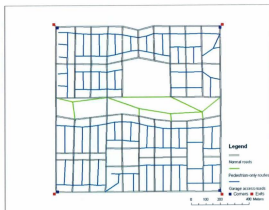


Figure 7.6: Neo-traditional neighbourhood 2 (NU2)

Figure 7.7 shows a fused grid neighbourhood design (FG) as proposed by CMHC. For automobiles, the neighbourhood contains only four blocks equal in size. But for pedestrians, the pedestrian-only routes throughout the neighbourhood make the effective block size much smaller. The original fused grid design (see Section 2.1) includes twinned arterials outside the residential area, with facilities located between the twinned arterials. These twinned arterials are omitted in the map here to make the map more comparable with the other six hypothetical designs. Facilities are assumed to be located at the corners of the neighbourhood or along the surrounding arterial depending on the experiments.

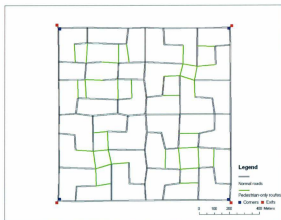


Figure 7.7: A fused grid neighbourhood (FG)

7.1.1 DESCRIPTIVE CHARACTERISTICS

Table 7.1 shows two of the physical characteristics of each of the seven neighbourhood designs. Grid-based neighbourhoods generally have greater road length (TG1, TG2, NU2) and smaller blocks (TG1, NU2) which normally mean more intersections. The road length numbers shown here only include normal roads (not pedestrian-only routes or garage access roads). The numbers in brackets means the length of garage access roads per square kilometre for the new urbanism designs.

Table 7.1: Physical characteristics of the hypothetical neighbourhoods

<i>Type</i>	<i>Map</i>	<i>Road length (km) per square kilometer</i>	<i>Intersections per square kilometre</i>
Traditional grid	TG1	21.4	93.8
	TG2	18.9	56.3
Post-war suburban	PW1	16.6	57.8
	PW2	19.1	73.4
Neo-traditional	NU1	16.6 (11.3)	64.1
	NU2	19.7 (13.0)	112.5
Fused grid	FG	16.4	68.8

Table 7.2 shows how the road network characteristics influence access distances to local facilities, potential stops for automobiles and crossings for pedestrians. With looping roads and cul-de-sacs, post-war suburban designs have the highest average access distance to local facilities for both automobile and pedestrian trips. With the use of

pedestrian-only routes, the new urbanism designs often feature slightly lower access distance for pedestrians than for automobiles. The fused grid seems to be most successful at maximizing the difference between driving and walking access distances.

Table 7.2: Characteristics of the artificial neighbourhoods

<i>Type</i>	<i>Map</i>	<i>Average travel distance to local facilities for automobiles (m)</i>	<i>Average travel distance to local facilities for pedestrians (m)</i>	<i>Average stops for vehicles</i>	<i>Average crossings for pedestrians</i>
Traditional Grid	TG1	815	815	8.1	5.1
	TG2	818	818	7.0	3.2
Post-war Suburban	PW1	966	966	6.1	4.3
	PW2	908	908	7.5	4.7
Neo-traditional	NU1	855	826	6.1	4.0
	NU2	804	788	8.5	5.6
Fused grid	FG	871	810	8.2	3.7

For automobiles, the second traditional grid design (the one with larger blocks, TG2), the post-war suburban designs (PW1, PW2), as well as the first neo-traditional design (NU1), have lower number of potential stops due to their automobile-friendly characteristics including large blocks and looping roads which decreases the number of intersections in the neighbourhood. The first traditional grid design (TG1), the second neo-traditional design (NU2) and the fused grid design (FG) show higher number of

stops, due to the small block size used in TG1 (Figure 7.1) and NU2 (Figure 7.6) and the extensive use of cul-de-sacs in FG (Figure 7.7). Road crossings for pedestrians show a different picture, with fused grid, post-war suburban, NU1 and TG2 (the grid design with larger blocks) showing fewer crossings while the two designs with small blocks (TG1 and NU2) showing higher crossing numbers. Note that vehicle stops and pedestrian crossings are calculated in different ways. The model does not contain a traffic light module, and every intersection is considered a possible stop for automobiles. Pedestrian crossings, on the other hand, are calculated based on the detailed route of each agent. For example, if the pedestrian is on the right side of a road and turning right, the number of crossings is 0. Note that the numbers in Table 7.2 are calculated based on a uniform distribution of the population inside the neighbourhoods, and an even distribution of traffic towards the four corners/exits of the neighbourhood.

Figure 7.8 compares the difference in travelling distances between driving and walking in PW2, NU1, NU2 and FG. The graphs are created by plotting (x, y) points where x represents the distance travelled inside the neighbourhood for the driving mode, while y represents the distance travelled inside the neighbourhood for the same trip if the walking mode is chosen. The automobile oriented post-war suburban design shows little benefits for pedestrians, and the grid-based neo-traditional design (NU2) shows only small benefits for pedestrians. The larger variance may be explained by the grid design and the small block size which makes pedestrians more likely to choose a sub-optimal route. The neo-traditional design with looping roads (NU1) and the fused grid design

present much greater benefits for pedestrians. The fused grid design does especially well, with the walking distance almost always equal or lower than the driving distance.

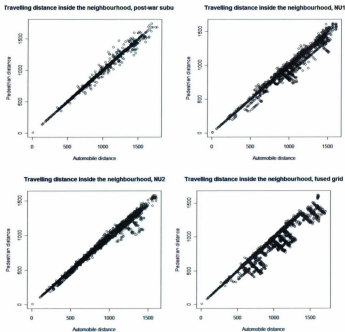


Figure 7.8: Comparison of driving versus walking distance to facilities/exits

7.1.2 THE "REPLACEMENT" EXPERIMENTS

To examine the influence of neighbourhood design on traffic patterns, the first set of experiments assumes that a current neighbourhood is transformed into one of the seven hypothetical neighbourhood designs, while its population and trip demand remain unchanged. The simulation model calculates new trip modes and routes based on personal characteristics and neighbourhood and traffic conditions. The population from TAZ 242 is used, as the TAZ is roughly 0.64 square kilometres in area (excluding Humpton Park; see Figure 5.2), which is the same size as the hypothetical neighbourhoods.

Table 7.3 shows the prediction of modal split and other traffic-related characteristics for each of the seven designs. Note that the original TAZ 242 is mostly a traditional grid neighbourhood, and traffic can enter and exit from the neighbourhood from around 20 exit points (see Figure 5.2). Such traffic is assigned to use the closest counterpart (exit) in the hypothetical neighbourhoods.

Table 7.3: Modal split and other predictions based on the "replacement" experiments

<i>Prediction</i>	<i>TG1</i>	<i>TG2</i>	<i>PW1</i>	<i>PW2</i>	<i>NU1</i>	<i>NU2</i>	<i>FG</i>
Driving (percentage)	71.2	71.1	73.2	71.6	72.5	66.9	66.6
Transit (percentage)	11.1	11.3	10.8	11.0	10.4	11.3	10.8
Walk (percentage)	17.7	17.6	15.9	17.4	17.1	21.8	22.7
Total vehicle Distance inside the neighbourhood (km)	2847	2839	3390	3135	2990	2636	2849
Total pedestrian Distance inside the neighbourhood (km)	1154	1189	1249	1247	1090	1298	1338
Pedestrian encounter	6655	7453	5785	6038	3967	6033	6515
Pollution Exposure Index	4.8	6.74	9.69	8.01	4.04	2.29	4.18

The modal split prediction as shown in the first three lines of Table 7.3 shows that post-war suburban style neighbourhoods tend to produce more automobile trips. On the other hand, the grid-based new urbanism design (NU2) and the fused grid design produce significantly more pedestrian trips. Characteristics that favour walking and discourage driving for the new urbanism and fused grid designs include shorter average pedestrian distance to local facilities and exits, more vehicle stops and lower pollution exposure. The pollution exposure index is calculated as:

$$P = \alpha \sum_i T_i t_i$$

where α is a scaling parameter to make the numbers more readable. T_i refers to the hourly automobile traffic volume on the i^{th} street of the pedestrian's route at the time period of the trip, and t_i refers to the duration of time that the pedestrian stays (walking) on the road. The index shows vast differences between different regions, with the two post-war suburban designs showing much higher exposure than any other neighbourhood types, due to the concentration of both automobile and pedestrian traffic on the collector roads. The traditional grade designs show lower (better) exposure index values, while the neo-traditional and fused grid designs show the lowest values. The NU2 design enjoys the lowest exposure, as the pedestrian-only routes and extensive garage access roads provide pedestrians a walking environment where automobile traffic volume is minimal. The grid designs also have the effect of distributing traffic more evenly among the streets, thus each street has lower automobile traffic volume.

Post-war suburban neighbourhoods also have much higher total vehicle distance (driven inside the neighbourhood) partly due to the higher driving distance to local facilities and exits as shown in Table 7.2. On the other hand, even with lower average walking distance to local facilities and exits, the NU2 and FG designs still show much higher total pedestrian distance.

The results for pedestrian encounter numbers show a different story. While the prediction shows that post-war suburban designs have the lowest percentage of pedestrian trips, the pedestrian encounter counts for these regions are actually close or higher than those for the new urbanism and fused grid designs. The reason should be the same as that for the high pollution indices for these regions. With a hierarchical street system, the pedestrian traffic level is likely to be higher on the collector roads, and the higher concentration of pedestrians on such roads leads to more chance of encounter. On the other hand, the new urbanism and fused grid designs often have significantly more road surfaces (when garage access roads and pedestrian-only routes are included) which has the effect of dispersing pedestrian flows.

The first new urbanism design (NU1) shows disappointing results in the prediction with a low percentage of pedestrian trips. There are several reasons for this. While the design provides relatively short access distances to facilities, the average walking distance to local facilities is higher than those of all grid-based designs and only lower than those of the two post-war suburban designs. On the other hand, the design is also automobile friendly, with the lowest number of average stops (even lower than the numbers for the two post-war suburban designs).

The results show that for the same neighbourhood type, different implementation still has a large influence on traffic characteristics. For example, the larger block used in TG2 creates significantly higher pollution exposure comparing to TG1. The loop based new urbanism design (NU1) shows much lower share of pedestrian trips than its grid-based counterpart (NU2).

With the pedestrian encounter and pollution exposure results in mind, it would be interesting to see where in the neighbourhood the encounter or the exposure happens. Figure 7.9 shows the simulation result for the morning peak period for TG2, PW1, PW2, NU1, NU2 and FG respectively. The maps are created by marking the locations (using small red circles) where there are other pedestrian agents pass within 25 metres of the pedestrian agent in question during a 20-second time interval. Note that the model only counts the first such encounter for any two pedestrians during a trip, to avoid repeatedly count encounters in scenarios like when two pedestrians walk on the same road towards the same direction (in such a scenario, it is likely that they will be within 25 metres of each other for many 20-second intervals).

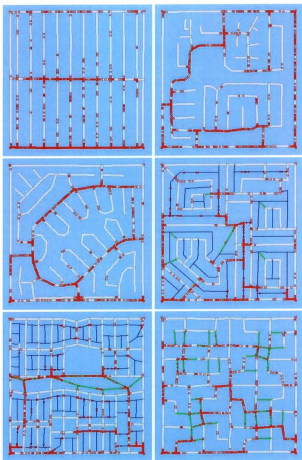


Figure 7.9: Spatial patterns of pedestrian encounter

(First row: TG2, PW1; Second row: PW2, NU1; Third row: NU2, FG)

Figure 7.9 shows that for the grid design and the post-war suburban designs, pedestrian traffic concentrates on the collector roads where high probabilities of pedestrian encounters occur. The NU1 design has an extensive network of garage access roads, but with the looping road network, these roads often do not represent an optimal path to the facilities or exits. Thus many pedestrian encounters still happen on normal roads. The NU2 design shows the benefit of the grid design. With such design, pedestrians can efficiently make use of the garage access roads and pedestrian-only routes, and most pedestrian encounters occur on these two types of roads/routes. The fused grid design does have the benefit of providing shorter access to facilities for pedestrians and the pedestrian paths provide a good environment for many pedestrian encounters, but with the design of four blocks inside the neighbourhood separated by internal arterial roads, pedestrian traffic still has to go through the intersection of these roads (at the center of the map FG).

With automobile traffic likely to be concentrated on the collector roads or internal arterials for some neighbourhood designs, automobile emissions are also likely to be concentrated on these roads. The pollution concentration maps are created by marking the locations where an automobile moves through in any ten-minute period (*i.e.* after ten minutes the marker is removed). Figure 7.10 shows an example of the ten-minute moving average of the vehicular traffic flow as represented by the number of markers on the map.

Figure 7.11 illustrates the spatial patterns of pollution concentration for TG2, PW1, PW2, NU1, NU2 and FG at the time when the 10-minute moving average value is the highest during the morning peak time. All the neighbourhood designs shown here

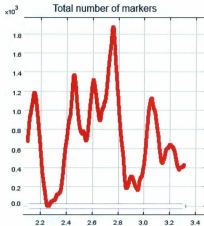


Figure 7.10: traffic flow in the morning peak period (10-minute moving average)
 (x axis shows the number of minutes ($\times 10^2$) since 3:30AM)

have the emissions concentrated on the collector roads or internal arterial roads. Comparing the maps with the pedestrian encounter maps (Figure 7.9), it is clear that the new urbanism designs (especially the grid-based NU2 design) and the fused grid design benefit local residents by separating automobile and pedestrian traffic. Note that the thematic maps are meant to illustrate the spatial pattern of automobile emissions and the locations where higher level of pedestrian exposure to automobile emissions are likely to happen. Actual pollution concentration level is influenced by vehicle types and speed, and factors influencing emission dispersion rate including building height and wind speed.

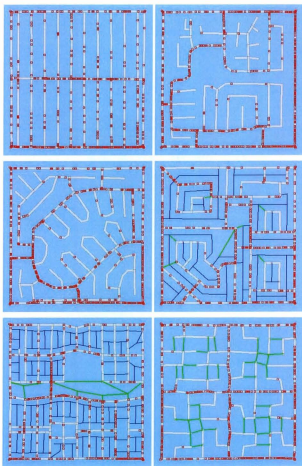


Figure 7.11: Pollution concentration estimation

(First row: TG2, PW1; Second row: PW2, NU1; Third row: NU2, FG)

Peak traffic volume on the roads is also examined in the model. With the small neighbourhood size (800×800 metres) in mind, serious congestion is unlikely to happen. But high traffic volumes on certain streets also mean increased emission concentration and higher collision risk for pedestrians. Figure 7.12 shows the peak traffic volume during the morning peak period for each road in the neighbourhoods. The width of the road displayed in the graphs depicts the highest traffic volume during any 10-minute period from 7:00AM to 9:00AM, with the five street sections with the highest traffic volume highlighted in red. As shown in the graphs, high traffic volumes are likely to occur on the connector roads which either connect the residential area to the arterial roads or connect two residential areas inside the same neighbourhood. As expected, the peak traffic volume is still low, with the maximum 10-minute traffic volume around 20 to 40 for all neighbourhood designs.

7.1.3 LOCATION AND NUMBER OF FACILITIES

The trip and traffic patterns inside urban neighbourhoods are also influenced by the location of facilities both inside and outside the neighbourhood. For example, if the facilities inside the neighbourhood are concentrated at one corner of the neighbourhood, then higher traffic volume is likely to occur at or close to this corner. Location of the facilities outside the neighbourhood normally reflects the location of the neighbourhood in the city. For example, if a neighbourhood is located at an extreme corner of a city, most traffic is likely to enter/exit from the exit(s) that are closer to the employment or

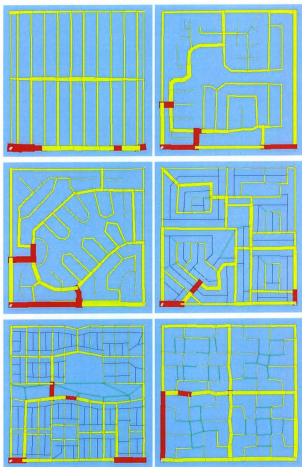


Figure 7.12: Peak traffic during morning peak time
 (First row: TG2, PW1; Second row: PW2, NU1; Third row: NU2, FG)

commercial center (or the main highway that leads to these centers). Many suburban neighbourhoods have only one or two connection roads to the main highway system, which is likely to cause the same effect, as outgoing traffic is forced to use these limited number of exits.

To test and highlight the influence of facility locations, three extreme scenarios are tested: In the first scenario ("even-distribution"), it is assumed that inside facilities are evenly distributed among all corners of the neighbourhood, while outgoing (and incoming) traffic is also evenly distributed among the exits (*i.e.* the four exits of the neighbourhood will see equal volume of outgoing and incoming traffic). This represents the scenario where the neighbourhood has a central location in the city, and inside facilities are also evenly distributed. In the second scenario ("one-exit"), it is assumed that all outgoing and incoming traffic use only one exit, and all inside facilities are also located at the corner close to the same exit. This represents the scenario where the neighbourhood is located in a remote corner of the city (or there is only one connection road to the road system outside), and all facilities are also located close to the exit point. This scenario, while extreme, represents the reality faced by many suburban neighbourhoods at the outskirts of the city. For example, for TAZ 501 in Ottawa (see Figure 5.7), most automobile traffic is likely to use Stonehaven Dr. as it is the only road that has good connection to the highway system and to the facilities inside and outside the neighbourhood. In the third scenario ("opposite-exits"), it is assumed that all inside facilities are concentrated at one corner of the neighbourhood, while all outgoing/incoming traffic uses the exits on the opposite side of the neighbourhood. While

other scenarios will also provide insights into the problem, these three extreme situations will help us understand the influence of facility locations more directly.

Table 7.4 shows the predictions for the share of pedestrian mode for the three test scenarios. Note that in the one-exit experiments, the lower left corner of each of the hypothetical neighbourhoods was used, while for the opposite-exits experiment, it is assumed that local facilities occupies the lower left corner, while outgoing/incoming trips use the exit at the upper right side of the neighbourhoods.

Table 7.4: Influence of facility locations

<i>Scenario</i>	<i>TG1</i>	<i>TG2</i>	<i>PW1</i>	<i>PW2</i>	<i>NU1</i>	<i>NU2</i>	<i>FG</i>
One exit	16.8	17.0	16.2	16.9	16.7	20.8	21.4
Opposite exits	16.9	17.1	14.2	18.8	16.9	21.9	22.0
Even distribution	17.7	17.6	15.8	17.5	17.1	22.1	22.7

The table shows some interesting results. Most designs benefit from an evenly distributed traffic flow, with the share of pedestrian mode increasing when the corners/exits are more evenly used. However, the results show that the PW1 design benefits from the one-exit scenario, while suffers from the use of opposite exits. The PW2 design, on the contrary, benefits most from the use of opposite exits. Detailed analysis shows that the seemingly surprising results are related to the details of the road network layouts in these neighbourhoods. For example, in map PW1 (Figure 7.3), the lower part of the neighbourhood is almost entirely cut off from the upper part. Residents

in the lower part of the neighbourhood face a significantly longer travelling distance to travel to the upper right corner of the neighbourhood. Compared to the scenario where all trips go to the lower left corner of the neighbourhood, average travelling distance increases from 830 metres to 1076 metres. The poorly connected residential area means that residents have to travel a much longer distance to reach certain corners of the neighbourhood. The average travelling distance is 966 metres for the "even-distribution" scenario, which is still much higher than that of the "one-exit" scenario (830 metres). On the other hand, the "opposite-exits" scenario benefits the PW2 design (Figure 7.4), because the design features connector roads close to these two exits (and relatively further away from the other two exits – upper left and lower right), and the inside region of the neighbourhood is better connected compared to PW1, which means pedestrians do not have to walk long distances on the arterial roads (where the traffic volume is also high) to reach certain corners of the neighbourhood.

The spatial patterns of pedestrian encounters vary dramatically under the three extreme scenarios. For the "one-exit" scenario (Figure 7.13, right), areas of the neighbourhood that are away from the exit see much less chance of pedestrian encounters. Pollution concentrations also show the same pattern, except that even heavier concentration occurs on the arterial roads since automobile traffic cannot use pedestrian-only routes. Peak street traffic volume for each neighbourhood increases to 50-70 for any 10-minute period, often doubles the volume in the situation with a uniform distribution of facilities. Note that many pedestrian only routes in Figure 7.13 have few or none pedestrian encounters showing. This is most likely due to how the location marking

works in the software, as it only marks the location where any two agents “first meet”, as explained in Section 7.1.2.

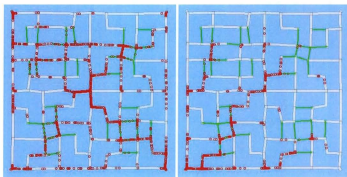


Figure 7.13: Changes in encounter location

(Left: the “even-distribution” scenario, right: the “one-exit” scenario)

With the uneven traffic distribution and heavier traffic flow (both automobile and pedestrian) on few streets, both pedestrian encounter counts and pollution exposure index values increase dramatically for all regions (Table 7.5).

Table 7.5: Changes in pedestrian encounter and pollution exposure

<i>Measures</i>	<i>Scenario</i>	<i>TG1</i>	<i>TG2</i>	<i>PW1</i>	<i>PW2</i>	<i>NU1</i>	<i>NU2</i>	<i>FG</i>
Pedestrian encounter	Even distribution	5790	6642	5944	6031	3880	5772	6113
	One exit	8873	9262	8572	9310	6989	9496	11099
Pollution exposure	Even distribution	4.0	5.8	9.5	7.5	3.6	1.9	3.7
	One exit	9.6	13.2	17.6	16.6	9.9	5.1	7.9

All experiments above are carried out based on the assumption that local facilities are at the four corners of the hypothetical neighbourhoods. In reality, local facilities would be more dispersed. This is particularly true for traditional grid neighbourhoods. Experiments are carried out to find out the influence of increasing facility locations. Table 7.6 shows the simulation result for the traditional grid design TG1. Note that in the case of 8, 12 and 16 facility locations, these locations are still evenly distributed along the surrounding arterials (*i.e.* 2, 3 or 4 locations on each side).

Table 7.6: The effect of increasing facility locations

<i>Scenario (number of facility locations)</i>	<i>Average pedestrian distance to local facilities (m)</i>	<i>Average crossings for pedestrians</i>	<i>Pollution exposure index</i>	<i>Peak traffic volume</i>	<i>Pedestrian encounters</i>	<i>Share of pedestrian mode (percentage)</i>
4	815	5.1	4.0	23	5790	17.7
8	721	5.1	3.9	23	5557	17.7
12	685	5.0	3.9	23	5271	17.6
16	678	5.0	3.9	23	5249	17.6

With more facility locations, average access distance to the facilities steadily decreases. The average number of road crossings, the pollution exposure index and peak traffic volume remain basically stable. Pedestrian encounter numbers decrease as pedestrians are more dispersed in the neighbourhood. The combination of these changes leads to a basically stable share of pedestrian mode travels. The numbers also show the

pattern of diminishing returns, as more facility locations beyond 12 only brings slight decrease in access distance. Note that these experiments are based on the assumption that residents will choose a random facility location in the neighbourhood, not the nearest one. If agents choose the nearest location, the benefits for pedestrians will be more evident.

Other than the location, the number of facilities available may also change the model outcomes. While the influences of increased local facilities on different types of travel are debated (for example, research shows that work trips are less likely to be influenced by increased local job opportunities, see Section 2.1), it is believed that elastic trips such as shopping and service trips are likely to be influenced by changes in local facility provision. Based on the gravity sub-model (see Section 6.5), it is estimated that if the number of local shopping/service facilities doubled, the number of shopping/service trips ending inside TAZ 242 would increase from 156 to 267. Using the gravity model prediction together with the "replacement" experiments, the results (Table 7.7) show that for all designs, the share of pedestrian mode travels remains stable or only sees minimal increases. There are several reasons. First, the survey data show that shopping/service trips ending inside the TAZ only account for a small percentage of all trips (around 2% for TAZ 242). Second, only around half of all shopping/service trips are direct shopping/service trips (*i.e.* trips that start from home, stop at a shopping/service facility and then end at home). Many shopping/services activities are done on the way to work or back from work. Third, many shopping/service trips ending outside the TAZ (especially those to the nearby TAZs) are already pedestrian trips. Fourth, considering residents' personal preferences, a shorter trip length does not necessarily mean that a driving trip

will be turned into a pedestrian trip. Thus, while more shopping/service trips are predicted to be ending inside the TAZ, the travelling modes of these trips do not necessarily change.

Table 7.7: Influence of increasing local facilities

<i>Design</i>	<i>Share of pedestrian mode travels</i>	<i>Predicted share of pedestrian mode travels with doubled local shopping/service facilities</i>
TG1	17.7	17.7
TG2	17.6	17.5
PW1	15.9	15.9
PW2	17.4	17.4
NU1	17.1	17.3
NU2	21.8	22.1
FG	22.7	22.9

7.1.4 ROAD CHARACTERISTICS

The characteristics of the road network also influence travel decisions and traffic patterns. For example, the availability of sidewalks and pedestrian-only routes and the characteristics of road crossings may influence pedestrian safety level. The number of intersections and traffic controls influences pedestrian safety and automobile speed as well as automobile emissions. Changes in pedestrian safety and automobile speed will in turn influence route and mode choices.

Of these characteristics, pedestrian-only routes are probably the most influential factor for pedestrians, as the availability of pedestrian-only routes directly (and often dramatically) changes access distance to facilities, number of crossings, exposure to emissions and safety level for pedestrians. In this section, experiments are carried out to simulate the influence of the availability of pedestrian-only routes.

For the experiments, three designs are used: the post-war suburban designs PW1 and PW2, and the fused grid design FG. The PW1 and PW2 designs are modified to include a pedestrian-only routes system in both designs. Figure 7.14 and Figure 7.15 show the PW1 and PW2 designs with pedestrian-only routes linking the cul-de-sacs or the looping roads.



Figure 7.14: The PW1 design with added pedestrian-only routes



Figure 7.15: The PW2 design with pedestrian-only routes

Experiments are set up to compare the influence of the designs in the following scenarios:

1. The pedestrian-only routes (PORs) shown in the maps are available for use by pedestrians;
2. The PORs shown in the maps are not available for use (*i.e.* assuming that the pedestrian-only routes are eliminated);
3. The PORs shown in the maps can be used by both automobile and pedestrian traffic (*i.e.* assuming that those routes are not pedestrian-only, but just normal roads).

The simulation results are shown in Table 7.8 for the new PW1 design, Table 7.9 for the new PW2 design and Table 7.10 for the fused grid design. To give a more general

evaluation of the designs, the experiments are based on the “even-distribution” scenario (*i.e.* all corners/exits of the neighbourhoods see equal amount of traffic).

Experiments with the PW1 design show that with PORs available, pedestrians enjoy shorter access distance to facilities, fewer crossings and lower pollution exposure (Table 7.8). As a result, the share of pedestrian mode travel increases, but the chance of a pedestrian encounter is slightly lower, as pedestrians are more dispersed with the increased road/route length. If these PORs are considered normal roads (*i.e.* they can be used by automobiles as well), then pedestrians will see slightly higher crossing numbers, higher pollution exposure and even fewer chances of pedestrian encounter, as pedestrians are less likely to be attracted to (and concentrated) on such roads.

Table 7.8: Testing the influence of pedestrian-only routes with PW1

<i>Scenario</i>	<i>Average pedestrian distance to facilities</i>	<i>Average pedestrian crossings</i>	<i>Share of pedestrian mode</i>	<i>Pedestrian encounter</i>	<i>Pollution exposure index</i>	<i>Peak traffic in any 10-min period</i>
PORs available	917	3.9	17.4	5872	6.7	28
PORs not available	967	4.3	15.8	5944	9.5	28
PORs as normal roads	917	4.0	16.2	5117	7.5	28

The experiments with the PW2 design show similar results, but the benefits for pedestrians are less significant (Table 7.9). With PORs, pedestrians will still benefit from shorter access distance, fewer crossings and lower pollution exposure, but the change is not as significant as seen in the PW1 design. With a much lower chance of pedestrian encounters, the share of pedestrian mode remains unchanged. On the other hand, if these PORs are considered normal roads, the benefits for pedestrians are even less significant. With an even fewer chance of pedestrian encounters, the share of pedestrian mode is predicted to decrease. Experiments with both PW1 and PW2 designs show that the peak traffic volume is not influenced by introducing more roads (when PORs are considered normal roads).

Table 7.9: Testing the influence of pedestrian-only routes with PW2

<i>Scenario</i>	<i>Average pedestrian distance to facilities</i>	<i>Average pedestrian crossings</i>	<i>Share of pedestrian mode</i>	<i>Pedestrian encounter</i>	<i>Pollution exposure index</i>	<i>Peak traffic in any 10-min period</i>
PORs available	887	4.2	17.5	4785	6.5	25
PORs not available	908	4.7	17.5	6031	7.5	25
PORs as normal roads	887	4.3	16.5	4511	6.6	25

On the other hand, pedestrian-only routes play a much more important role in the fused grid design (Table 7.10). Without the PORs, average pedestrian distance to facilities is much higher, and the average number of road crossings for pedestrians increases by 38%. The chance of pedestrian encounter is higher, as pedestrians are more concentrated on the arterial roads. But this also leads to a pollution exposure index that more than doubles the original prediction (when PORs are available), as pedestrian are forced to use and be concentrated on the same arterial roads as the automobile traffic. As a result, the share of the pedestrian mode is significantly lower. If the PORs are considered normal roads, the share of pedestrian mode is predicted to be higher than when PORs are not available, but still much lower than when PORs are available, as pedestrians face higher pollution exposure and much lower chance of pedestrian encounters in this scenario.

Table 7.10: Influence of pedestrian-only routes (FG)

<i>Scenario</i>	<i>Average pedestrian distance to facilities</i>	<i>Average pedestrian crossings</i>	<i>Share of pedestrian mode</i>	<i>Pedestrian encounter</i>	<i>Pollution exposure index</i>	<i>Peak traffic in any 10-min period</i>
PORs available	810	3.7	22.7	6113	3.7	20
PORs not available	874	5.1	17.3	7507	8.4	23
PORs as normal roads	810	3.7	18.6	4337	4.1	20

While the availability of pedestrian-only routes has different impacts on different neighbourhood designs, it is shown that introducing pedestrian-only routes, especially at strategic locations, will generally provide benefits to pedestrians by decreasing walking distance to facilities, road crossings and pollution exposure. For example, the use of pedestrian-only routes in the fused grid design successfully leads a pedestrian-friendly environment with short access distance to facilities, very low pedestrian crossings and pollution exposure, and high pedestrian encounter possibilities.

Figure 7.16, Figure 7.17 and Figure 7.18 show the comparison of spatial patterns of pedestrian encounter locations with pedestrian-only routes (right) or without (*i.e.* pedestrian-only routes are not used, left) for the PW1, PW2 and FG design respectively.

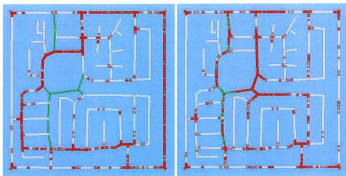


Figure 7.16: Influence of pedestrian-only routes for PW1
(Left: PORs not used, right: PORs used)



Figure 7.17: Influence of pedestrian-only routes for PW2
(Left: PORs not used, right: PORs used)

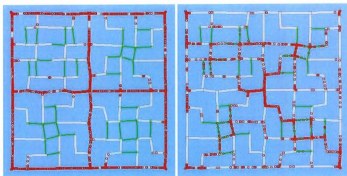


Figure 7.18: Influence of pedestrian-only routes for FG
(Left: PORs not used, right: PORs used)

For all the designs shown, pedestrian-only routes provide a good environment for possible pedestrian encounters. Without such pedestrian-only routes, pedestrians are forced to concentrate on the roads where the volume of automobile traffic and emission concentration are also higher. The concentration of pedestrians on the pedestrian-only routes is more evident in PW1 than PW2, as the PORs in PW1 provide more significant benefits. The graphs show that pedestrians make more use of pedestrian-only routes when such routes provide continuous, direct and shorter access to facilities. The use of pedestrian-only routes creates a significantly different spatial pattern of pedestrian encounters, especially for PW1 and FG, which explains the big change in pollution exposure index in Table 7.8 and Table 7.10.

7.1.5 POPULATION DENSITY

Neighbourhoods are normally designed to accommodate a specific density. For example, post-war suburban neighbourhoods normally have lower densities than new urbanism neighbourhoods. However, there is no specification or consensus on what population density each kind of neighbourhood design should have (Burton, 2002). Densities are also measured in different ways, sometimes without clear definition. For example, population/household density could be measured as the number of persons/units per hectare of total land area (Gross Density), or the number of persons/units per hectare of developed land area (Net Density).

Table 7.11: Neighbourhood density from different parts of the world

<i>Source</i>	<i>Density type</i>	<i>Study region</i>	<i>Value (person/ha)</i>	<i>Households/ha</i>
Forsyth <i>et al</i> , 2007	High density	Twin Cities, MN	>24.7	
~	Low density	~	<12.4	
Khattak and Rodriguez, 2005	New Urbanism	North Carolina	15.33	
~	Conventional neighbourhood	~	13.11	
Gordon and Vipond, 2005	New urbanism	Markham, ON	61	19.6
~	Conventional neighbourhood	~	36.6	11.1
Burton, 2002	Howard's Garden City	By design	180	45
~	Unwin's standards, used for most interwar housing	UK	120 – 150	30
~	Post-war new towns	Milton Keynes, UK	68	
~	Current new development	UK	47-94	
~	Planned density, 1970s	Singapore	1000	
~	Sustainable density advocated by Friends of the Earth		225 - 300	

Table 7.11 lists some density values from previous studies. It shows that neighbourhood density varies significantly in different regions and different countries, and that neighbourhoods built at different times also tend to have different density. Even neighbourhoods using the same type of design have different density in different implementations. It is also noted that different cultures may have different perceptions regarding density, and even the same density may be felt differently by different people and cultures (Rapoport, 1975; Scoffham and Vale, 1996). This different perception of density may be due in part to building height or lot size. Note that the density values in Table 7.11 are obtained from multiple sources which give no clear indication of whether these are gross or net density.

The study areas in Ottawa also have quite different population densities. For different neighbourhoods, density not only appears as gross density, street-level density (the number of houses per given length of street) is also important. Due to different road layouts, different neighbourhoods have different road lengths (and road length per square km area, as shown in Section 5.1.3 and Section 7.1.1) and different lot sizes. Thus the number of houses on a given length of street also differs. Table 7.12 shows density measures for the seven TAZs in Ottawa. Street-level density shows some interesting differences from gross density. For example, TAZ 434 has a lower gross household density than TAZ 242, but it has a higher gross population density, a similar street-level household density and a much higher street-level population density. TAZ 501 has a similar gross population density to TAZ 242 (36 vs. 33), but a much higher street-level population density (321.3 vs. 200.3). Compared to either gross density or net density,

street-level density is more directly perceivable by local residents and pedestrians. Street-level density also directly influences the number of pedestrians on a street section with a given length. For example, if the same percentage of residents chooses to walk on the streets at 6PM, areas with higher street-level density will see more pedestrians per kilometer of street than areas with lower street-level density.

Table 7.12: Density measures for the Ottawa TAZs

<i>Region</i>	<i>TAZ</i>	<i>Households (HH)</i>	<i>Population (P)</i>	<i>Area(ha)</i>	<i>HH/ha</i>	<i>P/ha</i>	<i>HH/km</i>	<i>P/km</i>
Westboro	242	1327	2710	82	16.2	33.0	98.1	200.3
	243	1842	4901	108	17.1	45.4	101.5	270.1
Barrhaven	433	2440	6570	108	22.6	60.8	169.9	457.4
	434	3832	10733	278	13.8	38.6	99.9	279.8
	435	2076	6645	122	17.0	54.5	105.7	338.3
Bridlewood	500	2861	8857	250	11.4	35.4	112.2	347.3
	501	3428	9393	261	13.1	36.0	117.3	321.3

A higher density of pedestrians on the roads will in turn translate into more chance of pedestrian encounters. Figure 7.19 shows the relationship between the number of pedestrian encounters and the population density. For the experiment the population in the test region is set to be a given percentage (from 10% to 200% with an interval of 10%, and 300%, 400%, 500%) of the initial value, and the same percentage of pedestrian trips are generated for each test. Results show that the number of pedestrian encounters follows a power law as density changes.

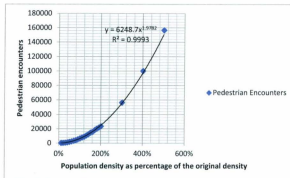


Figure 7.19: pedestrian encounter as a factor of density

As chances of pedestrian encounters increase with density, mode choice may also be influenced. Table 7.13 shows the results of density experiments. The range of densities used in the experiments are between 10 and 30 households per hectare, which represent a realistic density value range as shown in Table 7.12. Populations in the density experiments are generated based on survey data from TAZ 242.

In all the cases, the percentage of trips in pedestrian mode is relatively stable, and there is no clear pattern of change. While density increase brings more chances of pedestrian encounters, it also brings higher automobile traffic flow to the neighbourhood. With no changes in other neighbourhood conditions like facility accessibility and availability, the influences of automobile traffic and pedestrian traffic seem to be in balance regardless of density. This is in line with the finding of Fillion (2005) that density may only be effective when combined with other factors like proximity to quality transit

Table 7.13: Percentage of trips in pedestrian mode with different densities

Map	Density (HH/ha)				
	10	15	20	25	30
TG1	18.1	17.5	18.0	17.8	18.2
TG2	17.5	17.6	17.7	17.2	17.4
PW1	16.1	15.1	15.6	16.0	16.0
PW2	18.1	17.5	16.9	17.2	17.0
NU1	15.8	17.5	17.4	17.2	17.0
NU2	22.3	21.8	22.2	22.5	21.6
FG	22.2	21.9	22.6	22.2	22.2

service and large concentration of activity opportunities. Of course, in a real-world setting, feedbacks between population density and facility provision normally mean that more local facilities will appear (if allowed by zoning) with the increase of population density. Thus, the results also illustrate the need for a flexible zoning that allows facility creation.

7.1.6 POPULATION STRUCTURE

As discussed in Section 6.3, travel decision behaviour is influenced by population characteristics. Changing the composition of the population will also change the traffic patterns and ultimately the model outcomes. This can be investigated by replacing different TAZs with a particular neighbourhood design while keeping population

characteristics and density unchanged. Table 7.14 shows the results of a set of experiments using the fused grid design in place of five Ottawa TAZs. Note that the experiments are not done for TAZ 433 and 434, as the two TAZs are irregularly shaped and it is hard to give a meaningful estimation of how traffic flow would use each of the four corners in the hypothetical neighbourhood designs.

Table 7.14: Influence of population structure on percentage of trips in pedestrian mode

<i>TAZ</i>	<i>242</i>	<i>243</i>	<i>435</i>	<i>500</i>	<i>501</i>
Prediction with the original design	21.8	23.4	11.1	6.6	9.3
Prediction with the fused grid design	22.7	27.6	13.1	8.0	11.1

The results suggest that, while all TAZs will benefit from a more pedestrian-friendly design, the benefits are more evident for regions with fewer pedestrian-friendly facilities. For example, TAZ 243 has very few pedestrian-only routes, and it is predicted to see an 18% increase in the share of pedestrian mode. The increases in the share of pedestrian mode travel for the post-war suburban TAZs are also noticeable, but the increases may not be as significant as expected. The moderate increase for these regions (TAZs 435, 500, 501) may be due to two reasons. First, socio-economic characteristics of the population do influence mode choice behaviour. For example, people from suburban neighbourhoods may be more inclined to drive given the same driving distance and traffic conditions. Second, these suburban TAZs already have some pedestrian-friendly facilities. For example, TAZs 500 and 501 feature extensive pedestrian-only route systems which benefits local pedestrians.

7.2 BARRHAVEN: THE PLANNING SCENARIOS

Other than the hypothetical maps, three maps covering the Barrhaven area are also used in the experiments, with one map representing the actual layout of the Barrhaven area, and the other two representing two planning scenarios in the form of the neo-traditional design and the fused grid design. Note that in the maps, the blue coloured roads are access roads to garages as mentioned in Section 7.1, while the green coloured roads are pedestrian-only routes. These maps cover the majority of the Barrhaven area, except the area east of Greenbank Road and south of the railroad. Blue squares (“corners” as in the map) refer to possible facility locations while red squares refer to exit points.

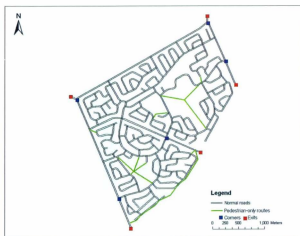


Figure 7.20: Barrhaven, the actual map (BH1)

The actual map of the Barrhaven area (BH1, Figure 7.20) shows a very typical post-war suburban design with hierarchical and curvilinear streets, cul-de-sacs and looping roads.

Figure 7.21 shows an overlay with a modified grid, a neo-traditional transformation of the layout (BH2). Loops and cul-de-sacs are eliminated in favour of grids with garage access roads. An extensive pedestrian-only route system (with parklands alongside the paths) is created in the neighbourhood.



Figure 7.21: Barrhaven, a neo-traditional transformation (BH2)

The fused grid overlay (BH3, Figure 7.22) shows typical features of the fused grid design as introduced in Section 2.1. The road system is formed with a continuous and open grid of arterials, with a discontinuous grid of minor collectors and local streets. Looping roads and cul-de-sacs are extensively used to ensure no through traffic, while pedestrian-only routes are created to make a continuous route system for pedestrians (CMHC, 2002).

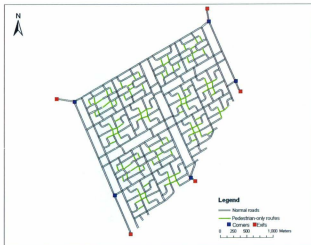


Figure 7.22: Barrhaven, a fused grid transformation (BH3)

7.2.1 GENERAL EVALUATION

Table 7.15 shows a list of general characteristics of the three different designs as well as predictions for the share of pedestrian mode. The grid-based neo-traditional design shows the most extensive road network, with much more road distance and more intersections than the other two designs. The design also has the highest average stops for automobiles, and the lowest pedestrian access distances to facilities. Pollution exposure is also significantly lower than that associated with the other two designs thanks to more dispersed traffic which means lower traffic volume on each street. While the number of pedestrian crossings is higher, the other advantages for pedestrians mentioned earlier still lead to the highest percentage of trips in pedestrian mode. Pedestrians will also see benefits from the fused grid design, but the predicted increase in share of pedestrian trips is less significant due to higher access distance to facilities and higher pollution exposure. The number of pedestrian encounters is also lower, but when considering the lower number of pedestrian trips, the average number of encounters per person is only slightly lower than with the neo-traditional design.

Note that the prediction in Table 7.15 is based on the assumption that facilities are allocated at the five "corners" of the neighbourhood. Thus, the fused grid design feature where facilities are located along the twinned arterial roads is not well represented. Experiments show that if facilities are evenly distributed along the twinned arterial, average pedestrian walking distance to local facilities will decrease from 1848 metres to 1333 metres for the fused grid design. As this number is still based on the assumption that residents will choose random facilities throughout the region, if all or most facilities that

residents need are located at the nearest twinned arterial, the prediction for the fused grid design would show better benefits for pedestrians.

Table 7.15: Descriptive characteristics of the three maps covering the Barrhaven area

<i>Map</i>	<i>Original</i>	<i>Neo-traditional</i>	<i>Fused grid</i>
Road distance (km)	45.0	68.7	55.2
Total intersections	183	402	341
Average stops for automobile traffic	12.2	15.6	15.5
Average crossings for pedestrian	7.3	9.4	8.1
Average distance to local facilities (automobile)	1905	1715	1918
Average distance to local facilities (pedestrian)	1840	1685	1848
Pedestrian encounter	147295	147687	109883
Pollution exposure index	68.8	29.2	46
Peak traffic volume in any ten-minute period	83	74	86
predicted share of pedestrian mode	10.4	14.9	11.7

Figure 7.23 shows the spatial patterns of pedestrian encounters for the neo-traditional design (BH2) and the fused grid design (BH3). Both designs show heavy concentration of encounters on the pedestrian path system, although the effect is more evident for the BH2 design, as the pedestrian-only routes are located at the center of the area.

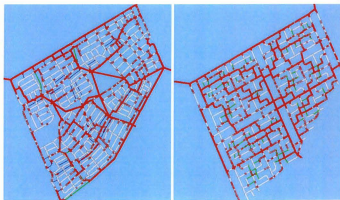


Figure 7.23: Spatial patterns of pedestrian encounters
(Left: BH2; right: BH3)

Figure 7.24 shows the spatial pattern of pollution concentration. Comparing to the spatial pattern of pedestrian encounters (Figure 7.23), it shows that both designs successfully create a greener environment for pedestrians and possible social interaction between pedestrians, as significant percentages of the encounters occur on the pedestrian-only routes and other roads with low vehicular traffic flows.

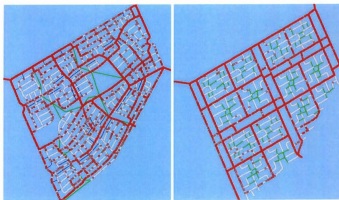


Figure 7.24: Spatial pattern of pollution concentration
(Left: BH2, right: BH3)

Figure 7.25 shows the predicted peak traffic volume on the streets for the two hypothetical designs. Peak traffic generally occurs at the corners where traffic enters and exits the region. The neo-traditional designs also sees higher traffic volume on the collector roads especially where the roads connect the residential areas separated by the parkland system (centre of the map). With no through traffic allowed inside the blocks, the fused grid design also shows high traffic volumes on the internal arterial roads. Note that the twined arterials in the fused grid design are supposed to be one-way only, but they are considered two-way in the model to simplify the route calculations in the model.

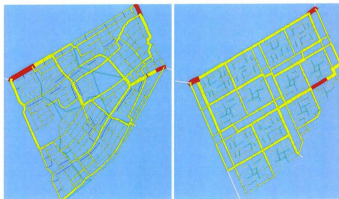


Figure 7.25: Peak traffic volume on the streets

(Left: BH2; right: BH3. The five streets with highest peak traffic volume shown in red)

7.2.2 INFLUENCES OF PEDESTRIAN-ONLY ROUTES

The extensive network of pedestrian-only routes clearly helps the new urbanism design and the fused grid design in attracting more pedestrian traffic. The experiment in this section explores the influence of the availability of such routes. The experiments are designed in the same way as those in Section 7.1.4, with three scenarios tested: Pedestrian-only routes available, pedestrian-only routes not available (*i.e.* eliminated from the maps), and pedestrian-only routes treated as normal roads (*i.e.* can be used by both automobile and pedestrian traffic). The results are shown in Table 7.16.

Table 7.16: Influence of the availability of pedestrian-only routes

<i>Map</i>		<i>Original</i>	<i>Neo-traditional</i>	<i>Fused grid</i>
Share of pedestrian mode	PORs available	10.4	14.9	11.7
	PORs not available	8.4	10.9	10.0
	PORs treated as normal roads	9.4	12.4	10.0
Average pedestrian crossings	PORs available	7.3	9.4	8.1
	PORs not available	7.7	10.3	10.1
	PORs treated as normal roads	7.4	9.5	8.1
Pollution exposure	PORs available	68.8	29.2	46.0
	PORs not available	101.5	74.3	98.1
	PORs treated as normal roads	76.2	38.7	48.1

Without pedestrian-only routes, all three neighbourhood designs see decreases in the share of pedestrian mode due to increased travelling distance, increased number of crossings and increased pollution exposure. The effect is particularly significant for the neo-traditional design, which again confirms the importance of placing pedestrian-only routes at strategic locations (as discussed in Section 7.1.4). With pedestrian-only routes treated as normal roads, the share of pedestrian traffic remains stable or moderately increases compared to the scenario where such routes are completely eliminated. In this scenario, pedestrian benefits from the better connectivity and lower automobile traffic

volume (as traffic is more dispersed thanks to more road length), but the benefits are not as significant as when these routes can only be used by pedestrians.

7.3 FINDINGS FROM THE EXPERIMENTS

The experiment results largely conform to what other studies have found and to what might be expected for the modelled neighbourhood designs. Among the designs studied, the neo-traditional neighbourhood designs and the fused grid design are found generally to be pedestrian-friendly, with fewer crossings, less walking distance to facilities, less traffic and pollution exposure and more social interaction opportunities for pedestrians. But some of these advantages also depend on the specific implementation. For example, the grid-based neo-traditional design (NU2) is linked to more pedestrian crossings, but shorter walking distance to facilities, than loop-based neo-traditional designs (like the NU1 design). Pedestrians often cannot make maximum use of the garage access roads or pedestrian-only routes in a loop-based design, as loops often mean more curved routes and significantly longer walking distance. Between the grid-based neo-traditional design and the fused grid design, the former is linked to less pollution exposure, but the chance of a pedestrian encounter is also lower, because in the former design, more road surfaces and shorter street sections limit the number of pedestrians that can be seen on each street section. The situation is improved by the provision of pedestrian-only routes at the centre of the neighbourhood, which not only serve as optimal shortest routes for pedestrians, but also create a green and safe environment for pedestrians and potential social encounters between pedestrians. The NU2 design and the

fused grid design are found to be associated with the highest share of pedestrian mode travel. Even with less walking distance to facilities, these two designs still show higher total pedestrian distances for the whole neighbourhood. On the other hand, the post-war suburban designs are linked to more automobile trips due to their automobile friendly characteristics including fewer stops for automobiles and longer access distance to local facilities for pedestrians. However, experiments also show that with appropriate modification (for example, adding a pedestrian-only routes system) a post-war suburban design can be made to be more pedestrian friendly.

Experiments show that pedestrians generally benefit from more local facilities, more even distribution of these facilities and the existence of a continuous pedestrian-only routes system, but such benefits can often be overshadowed by a complex web of other factors. Experiments with population density show that the relationship between population density and the chance of pedestrian encounter follows the power law. But the prediction also shows that the share of pedestrian mode remains basically stable with the increase in population density, as while the number of pedestrian encounters increase, the exposure to traffic and emissions also increases. The experiments with the location of local facilities show that with local facilities concentrated in one corner of the neighbourhood, the number of pedestrian encounters will significantly increase, but so will the exposure to automobile emissions. The example of the grid-based neo-traditional design shows a similar story: while more garage access roads and pedestrian-only routes mean pedestrians get better and shorter access to local facilities, the design also means more crossings for pedestrians. Furthermore, more roads mean less chance of pedestrian

encounter, but also less pollution exposure. The combined influence of these factors may lead to surprising results. For example, in the experiments with facility locations, while more facility locations certainly bring much shorter access distances for pedestrians, the predicted share of the pedestrian mode remains basically stable.

Such findings during the calibration and use of the model reflect the complex and stochastic nature of the phenomena in question and the simulation model itself. An urban neighbourhood is small, but it is a complex system in nature. While statistical analysis can reveal the influence of certain characteristics of the neighbourhood design on the traffic pattern inside the neighbourhood, a factor often does not act on its own, but rather acts together with other neighbourhood characteristics. It is the combination of all these contributing factors, including the factors that may not be included in the model, rather than an individual factor, that affects the modal split and traffic pattern in the neighbourhood. With an agent-based model like the one in this study, it is possible not only to visually present such dynamics using live traffic maps, graphs and histograms, but also to explore the underlying feedback mechanism and the bottom-up processes, such as the feedback between pedestrians and automobile traffic and the collective outcome of individual mode and route choice behaviour as presented in this study. As with all non-abstract models, there are always other feedback processes, factors and uncertainties which are not considered, or may not possible to be considered, in the model. In such cases, constants and randomizations are introduced to the model in the hope that they will represent a certain amount of unexplained factors, feedbacks or stochastic influences. The calibration process shows that such constants and randomizations often have the ability of

increasing model prediction accuracy (as shown by the constants in the utility functions) or improving the stability of the model output (as shown by the random taste variation values, and by the randomization in shortest route calculations).

In general, the calibration and experiments show that, compared to traditional methods, agent-based models enable the examination and analysis of not only the traffic pattern, but also the internal dynamics of neighbourhoods. And not only real world neighbourhoods can be simulated, test scenarios and hypothetical neighbourhoods can also be easily simulated, examined and analyzed.

CHAPTER 8: CONCLUSIONS AND FUTURE DIRECTIONS

This study is a first attempt in building an agent-based model that combines land use characteristics, transportation networks, and transport by both automobile and pedestrian modes, that considers personal preferences and characteristics, and that focuses on the neighbourhood scale. Using agent-based modelling techniques, the study intends to provide a scientific insight into the dynamics inside urban neighbourhoods.

8.1 THE MODEL AND THE SOFTWARE FRAMEWORK

Urban neighbourhoods are the basic units of cities, and neighbourhood designs are directly related to many aspects of daily life patterns and quality of life. While a neighbourhood is small, it has a number of constituent parts, including the road network and specific road characteristics as well as local traffic patterns; location and availability of local and external facilities; a local population with its particular characteristics, preferences and choice behaviour, and local social dynamics. These parts interact with each other in complex ways, with bottom-up processes, feedback influences and uncertainties forming the dynamics of neighbourhood traffic patterns and social life. Traditional research methods and techniques, while useful in explaining aggregate characteristics, often fail to reveal and explain the dynamics and internal processes that cause the dynamics. Agent-based modelling techniques and an integrated modelling framework are natural choices for the modelling of such systems, especially at smaller

scales like the neighbourhood level, where the dynamics of bottom up processes are easier to be identified and analyzed.

Customized software was developed for this study. The combination of the Repast simulation platform, OpenMap GIS toolkit and Java programming language allowed the production of a simulation model that is based on free and open source software, that is highly extendable (so that additional features can be added), and that can be easily customized and re-calibrated for use in other neighbourhood and transportation studies. The development of the software proves that, with proper techniques, it is possible to build a highly efficient agent-based model that is also low-cost, flexible and extendable.

Based on maps and data from the study area in Ottawa as well as data from other trip surveys, an agent-based simulation model was developed and calibrated to explore the influences of neighbourhood design on trip patterns inside urban neighbourhoods. As always, certain simplifications and assumptions were made during the model setup process to make the modelling of neighbourhood level traffic patterns feasible. However, these simplifications did not apparently seriously compromise the quality of the results. For example, experiments show that random allocation of households and facilities and the setting of pedestrian encounter distance have little influence on the output generated by the model and hence on the conclusions that can be reached. These experiments and the subsequent scenario-based experiments described in Chapter 7 show that it is possible to calibrate an agent-based model to simulate neighbourhood dynamics and the influence of neighbourhood design using trip survey data that are stripped of detailed street

locations. As many such data sets are freely available, modelling can be done without complex data collection and without the data use restrictions caused by privacy concerns.

Different approaches, including utility-based, activity-based and constraint-based approaches, have been used in the simulation of travel choice behaviour. This study in effect combined the advantages of these approaches, with utility measures, activity planning and constraints such as time and car availability considered in the calculation of route and mode choice. Utility is subjective, as taste variation always exists in a population. The study explored different utility functions with different forms of taste variation representation. The first approach, with taste variation represented by a normal distribution, and with the utility function built and calibrated completely from bottom up, proved able to generate reasonable modal split predictions (see Sections 6.1). While the results were less accurate when examined by population groups, the approach has the advantage of being simple and independent of specific population characteristics, and it can be further improved for use in abstract and conceptual studies. The MNL approaches (model 2.0 and 2.1, see Sections 6.3 and 6.4) show that with socio-economic characteristics directly included in the model, reasonable modal split predictions can be obtained and the results are much more accurate when examined by population groups. The MNL approaches also show that taste variation can be appropriately represented by socio-economic characteristics. The model formulation and calibration process shows that traditional research methods such as statistical analysis, and new techniques such as agent-based modelling, can be properly combined in creating a model that not only produces good predictions, but also is easier to calibrate.

As shown in Chapter 7, the software and the model show promising simulation capabilities and good results. Further improvements could increase the predictive accuracy and the usability of the model. For example, the current model uses expansion factors to generate the populations and trips. While the results from this approach are satisfactory, a trip generation module that generates trips and schedules from scratch would give the model more flexibility. It would enable the model to simulate induced or suppressed trip demand, and better explore the influences of self-selection. The calibration process shows that the model generates less accurate results for transit trips. While the reasons may be numerous (see Section 6.4), it is likely that a more accurate transit use prediction may be obtained by adding transit schedules and routes to the model. Similarly, car passenger trips may be added to the model to produce a more complete travel pattern.

8.2 APPLICATIONS AND POLICY IMPLICATIONS

This study demonstrates the evaluation of neighbourhood designs and configurations using agent-based modelling techniques. With the flexible and extendable software, studies and experiments can be done for other regions and other datasets. The modelling framework can serve as a prediction tool for real-world neighbourhoods, as well as a simulation and discovery tool for hypothetical and planned neighbourhood designs. By experimenting with different neighbourhood forms and different neighbourhood characteristics such as the number and location of facilities, the

characteristics of transportation networks and the demographic composition of residents, the simulation software is not only able to evaluate a neighbourhood design in general, but also able to evaluate detailed design specifications such as the availability and location of local facilities or pedestrian-only routes. Thus, this study also provides an alternative method for Traffic Impact Analysis (TIA).

Many large cities have city wide transportation models which predict traffic flow between TAZs on major roads and arterials. With proper integration, the model in this study can be combined with the city-level model to create a model that covers both local traffic dynamics within urban neighbourhoods as well as the dynamics of traffic flow between neighbourhoods or TAZs. The combination will also improve the predictive accuracy of the local model, as the city-level model can provide information such as TAZ-level traffic prediction and trip characteristics when the trip extends outside a neighbourhood, which it is not possible to directly obtain by means of the neighbourhood-level model.

In a more general sense, the model serves as a meso-level approach to urban and transportation simulation. As discussed in Section 2.3, existing urban and transportation models tend to focus either on the macro and aggregated metro-wide or even country-wide phenomena, or on the micro and detailed movement patterns of cars and pedestrians (for example, how the lane changing behaviour of drivers creates congestion, or how pedestrians move around obstacles or other pedestrians). The meso-level, where residents interact with each other, where feedback occurs between automobile and pedestrian traffic and between residents and their neighbourhood environment, and where local

patterns of modal split and traffic flow emerge, is often neglected. The development of a meso-level model not only helps to discover and analyze phenomena at its own level, it also makes possible an integration of micro-, meso- and macro-level models.

The integration of the micro- and meso-level models would provide the micro model with a realistic, dynamic and broader context, and would enable more flexible use of the micro model. For example, in the true micro models, traffic light controls and pedestrian crossing behaviour are often studied in the context of traffic flow and pedestrian safety. An integration of such true micro models with this meso-level model would provide the micro-level models with dynamic input of automobile and pedestrian traffic, and enable the observation of the collective outcomes at the neighbourhood scale. This should also improve the accuracy of the models at both levels. An integration of the meso- and macro- level models through, for example, the integration of this model and the city wide (TAZ-based) transportation model, would have a similar effect by providing the lower level model with a dynamic input and context, and by providing the higher level model with the local dynamics which in turn collectively form the global phenomena.

This study shows that, as the basic units of cities, urban neighbourhoods are complex and dynamic in nature. It can be expected that further complexity exists in the context of a whole city or a metropolitan area. The study shows that certain aspects of neighbourhood design are positively related to the selection of pedestrian mode, including the availability of pedestrian-only routes and the walking distance to facilities. However, the influence tends to be complex in nature. This suggests that urban policies and planning projects, while well-intentioned, could produce unexpected or even unwanted

results. Thus, for transportation and land use planning at the neighbourhood level in general, or even for small modifications of the neighbourhood road network such as adding new road links, a thorough analysis of the possible effects of planning regulations or new policies based on complex system theory is suggested. Neighbourhoods and cities need to be treated as the complex integrated systems they are. However, this does not mean that neighbourhoods and cities are not researchable or controllable. This study and many other studies of complex systems show that, with carefully selected variables and well formulated models, certain aspects of the system can be isolated, studied and explained. With proper formulation, this model, and its software framework, can be used for scenario testing of new urban policies or planning initiatives. It shall deepen our understanding of how new urban policies, new planning projects, or planned changes in the neighbourhood could influence trip and traffic patterns, how these patterns are distributed and change spatially and temporally, what are the likely causes underlying these patterns and changes, and consequently how the policies and plans can be improved.

This study concentrated on several aspects of neighbourhood life that are receiving widespread attention in today's world. With better informed planning of neighbourhoods, integrating the design advantages of the neo-traditional designs, the fused grid design and even certain characteristics from traditional grid and post-war suburban designs that are shown to be pedestrian and transit friendly, cities could be greener and more sociable, and their residents healthier and safer.

8.3 FUTURE RESEARCH DIRECTIONS

This study examined the influence of neighbourhood design on several neighbourhood phenomena that are directly related to daily lives, including social interaction opportunities, health, pedestrian safety, pollution and congestion. These aspects cover several academic fields including sociology, psychology, medicine, transportation and environmental studies. Further research could improve the presentation of the simulation results and the overall quality of the model. For example, social interaction opportunities may be more accurately represented by examining the characteristics of the corresponding residents and the time and location of these encounters. Walking distances and pollution exposure were used as indirect measures for health effects. These may be used to identify the health benefits or risks using findings from medical studies. Pollution or vehicle emissions can also be more accurately calculated by integrating an emission model which considers driving speed, vehicle type and traffic controls into the model.

It was proposed that this local-scale model can be combined with the metropolitan level travel forecasting model of Ottawa, which provides predictions on the number of trips from and to each traffic zone categorized by the type and mode of travel, and is calibrated for generating traffic for the coming years. However, while the metropolitan model is available, the software which the metropolitan model is based on could not be obtained. A future study integrating the use of that software would greatly increase the usefulness and probably also the accuracy of the model proposed in this thesis.

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APPENDIX I: SUPPORTING MODULES

MindSettings, MindTools, MindRouting, MindGlobal, MindGravity, MindData, MindCalibration and MindExperiment

8 support Java Classes are used in the software for miscellaneous computing job needed throughout the software.

MindCalibration

MindCalibration is used to run the software with maps and data from multiple neighbourhoods in batch mode.

MindData

MindData contains tools which statistically analyze the raw data and the output of the model.

MindExperiment

Similar to MindCalibration, MindExperiment is used to run the calibrated model using different maps and data under different scenarios.

MindGlobal

MindGlobal generates a map of trip flows between different TAZs/regions based on the raw data.

MindGravity

MindGravity is a module for analyzing the relationship between trip purpose and trip distance using the gravity model. It is used to simulate the changes in trip destinations when the amount of local facilities changes. The prediction of MindGravity can be fed into the MindInit module. This module also generates a map showing the distance zones from a given TAZ.

MindRouting

MindRouting is the shortest route generating module. The module generates the shortest route between specified nodes in a directed network. The algorithm is based on the famous (and widely used) Dijkstra's algorithm. The algorithm is modified to take the influence of sidewalk and pedestrian-only route availability, crossing count and road traffic condition into account. In addition to generating the shortest route, the module also specifies which side of the road a pedestrian agent will select. A multi-threaded version which utilizes modern multi-core CPUs is also available.

MindSettings

MindSettings contains all user settable parameters.

MindTools

The MindTools class is a collection of more than 40 methods that are used in other parts of the software. These methods are put in one place for easy maintenance of the code. The major methods are described below:

angle(): calculates the angle between any three points in a map in the counter-clockwise direction. This is used to sort the streets connected to one intersection, and in turn to calculate the number of crossings needed for pedestrians.

arrayToList(): provides a quick method for convert a small array to an ArrayList.

assignGeos(): assigns an actual location object to each household and agent based on the reference number to the location which is internally stored with each agent. This facilitates fast serialization.

buildRoadNetwork(): generates a directed network based on the GIS map.

carUse(): inquiries the car use schedule of the corresponding household to see if an agent can use a car for one of his/her round trip. The method returns a Boolean value "true" if a car is available for the time period of the round trip, and inserts the new round trip to the existing car use schedule.

createGeoNearNode(): creates a location object near a given node (intersection).

createGeos(): creates all the location objects needed in the software, and provides each of them with a unique ID.

databaseTableCount(): counts the number of tables in an Access database. This is used to generate new table without duplicate table names.

deepCopy(): generates a deep copy of an object. A multi-threaded version which utilizes modern multi-core CPUs is also available.

deserialization(): re-creates the objects that are saved in a file using the *serialization()* method.

distance(): calculates the distance between two points in metres.

edgesOnSameRoad(): determines if two given edges are referencing to the same road.

fastArrayClone(): a simple yet efficient array clone method which generates an identical copy of a small array.

geoQueueDistance(): takes a list of points (MindGeos) and returns the length of the line formed by these points. This is used in route length calculation.

getClosestGeoNearNode(): returns the closest point (MindGeo) near a specified node.

getDistanceGeoToGeo(): takes two points on the same road and returns the distance between them.

getDistanceGeoToNode(): calculates the distance between a point on the road and a specified end of the road (a node).

getGeoQueue(): takes a shortest route and returns the detailed list of points that forms the route. This is used to guide the movement of agents on the map.

getGeoQueueGeoToGeo(): returns the list of points between two points on the same road.

getGeoQueueGeoToNode(): returns the list of points between a point on the road and a specified end of the road (a node)

getNodeQueue(): returns the list of nodes that form the shortest route between any two nodes in a network. The initial network graph only contains the intersections as nodes. Any non-intersection points are dynamically added to the network graph as nodes (and they are removed from the network graph as soon as the shortest route is generated). This ensures that a shortest route can be generated between any two locations on a GIS map, and that the size of the network (the number of nodes) remains small, which improves the efficiency of shortest route calculation.

getRealEdgeIDQueue(): returns the real IDs of a list of edges. When non-intersection points are temporarily added to the network graph, temporary edges are created to connect these new points with existing nodes in the graph. These edges have temporary IDs as well as realEdgeIDs which reference to the corresponding roads.

getStatistics(): given a list of numbers, returns several statistical measures including mean, standard deviation, variance, skewness and kurtosis of the list.

initializeParameter(): initializes model parameters when the simulation begins.

ifWalking(): checks if an agent is walking.

log(): records properties of a household, its members and their trips to a pure text file for statistical analysis.

logger(): generates a logging machine which records specified model output values to a specified file. The output can either overwrite existing data in the file, or be appended to the end of the file.

modalSplitCount(): calculates the modal split given a list of agents.

modeChoice(): given a list of utilities, returns the choice based on the probability function. It can also be used to return the probability values.

modeChoicePreference(): generates a normal distribution with given mean and standard deviation values. This is used to generate taste variation.

newLocation(): given a point, a direction and a distance, returns the new location point.

numberToColour(): returns a colour based on the input value. This is used to create thematic maps where colours represent map properties. For example, different TAZs can be painted with different colours from a gray scale depending on their distances from the specified TAZ (see Section 6.5)

randomInRegionID(): given a list of regions and returns the probability that a random number would fall into any of these regions.

Randomization(): randomizes trip starting time and trip distances.

readDistanceMatrix(): reads the distance matrix between regions. In the Ottawa model, the distance matrix is provided by the city of Ottawa which provides shortest road distances between centres of TAZs.

readParameter(): reads the parameter files. A parameter file contains information regarding a corresponding map, including the list of non-residential streets, the location of local facilities, the number of households in the area and the distribution of facilities.

readRoadNetwork(): reads the road information from an map file, and creates a list of road objects. This method also calculates the map scale needed for correctly displaying the GIS map.

roundTripMovable(): determines if an existing round trip schedule in the car use list can be adjusted so that a new round trip can use the car, or if a new round trip schedule can be adjusted so it can be fit into the car use schedule.

serialization(): saves objects to a file. three serialization methods based on Java, XStream and JSX are possible.

tableExisted(): checks if a specified table name already exists in an Access database.

writeDatabase(): writes household, agent or trip information to an Access database.

zonalDistance(): returns the distance between regions (TAZs)

APPENDIX II: CORRELATION ANALYSIS RESULTS

Table II.1: Correlation analysis for the raw data

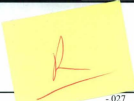
<i>Count</i>	<i>Auto</i>	<i>Transit</i>	<i>Walk</i>
Households	.791**	.781**	.640**
Vehicles	.984**	.643**	.141
Households in Detached Houses	.922**	.585**	.024
Households in Semi-Detached Houses	.326*	.249	.322*
Household in Townhouses	.614**	.549**	.127
Households in Apartments	-.055	.347*	.939**
Households in Other Residences	.012	.262	.214
Population	.909**	.804**	.447**
Male	.903**	.792**	.469**
Female	.908**	.809**	.421**
Age 4 and under	.744**	.335*	-.009
Age 5 to 9	.819**	.463**	-.004
Age 10 to 14	.849**	.601**	-.031
Age 15 to 19	.771**	.803**	.146
Age 20 to 24	.275	.607**	.918**
Age 25 to 34	.569**	.537**	.565**
Age 35 to 44	.840**	.634**	.219
Age 45 to 49	.862**	.725**	.240
Age 50 to 54	.808**	.768**	.158
Age 55 to 64	.700**	.709**	.372*
Age 65 to 74	.467**	.347*	.460**
Age 75 and over	.102	.100	.347*
Driver's License Holders	.883**	.804**	.518**

Transit Pass Holders	.676**	.969**	.291
Fulltime Workers	.902**	.777**	.361*
Part-time Workers	.711**	.744**	.403*
Students	.648**	.840**	.647**
Retirees	.482**	.410**	.408**
Homemakers	.775**	.351*	.014
Population with other job types	.515**	.631**	.726**
Child	.830**	.423**	-.009

(** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed))

Table II.2: Correlation analysis for the individual level average data

<i>Variables</i>	<i>Auto</i>	<i>Transit</i>	<i>Walk</i>
Households/Population	-.397*	.312	.482**
Vehicles Per Person	.812**	-.468**	-.735**
Male percentage	-.199	.012	.227
Female percentage	.199	-.012	-.227
Percentage of population 4 and under	.283	-.585**	-.380*
Percentage 5 to 9	.350*	-.529**	-.439**
Percentage 10 to 14	.382*	-.132	-.399*
Percentage 15 to 19	-.028	.512**	-.221
Percentage 20 to 24	-.668**	.422**	.788**
Percentage 25 to 34	-.320*	-.061	.310
Percentage 35 to 44	.163	-.431**	-.250
Percentage 45 to 49	.188	.227	-.180
Percentage 50 to 54	.184	.452**	-.140
Percentage 55 to 64	.117	.355*	.091
Percentage 65 to 74	.098	-.203	.055



Percentage 75 and over		-.027	.042
Percentage of population with driver's license	-.077	.247	.335*
Percentage of population with transit pass	-.355*	.949**	-.004
Percentage of population who are full time workers	-.037	.122	-.087
Part time workers	.087	.390*	.108
Students	-.480**	.558**	.482**
Retirees	.120	-.006	.027
Homemakers	.301	-.567**	-.352*
With other jobs	-.371*	.039	.487**
Children	.366*	-.643**	-.489**

(** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed))



